Construction site evacuation safety:

Evacuation strategies for tall construction sites

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Research report

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Alarm activation time	AAT
Bishopsgate	BG
Euclidean Projection Coefficient	EPC
Euclidean Relative Difference	ERD
End of response phase	ERP
Fire Safety Engineering Group	FSEG
Health and safety	HS
Health and Safety Executive	HSE
The Institution of Occupational Safety and Health	IOSH
Mechanical, electrical and plumbing	MEP
Occupants per metre per second	occ/m/s
Response time	RT
Start of activity stage	SAS
Secant Coefficient	SC
University of Greenwich	UoG

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Abstract

BACKGROUND:

The soaring scale of high-rise building construction – the number of projects and the size of the buildings – is reflected in the number of workers exposed to these demanding construction environments, and the potential for large-scale evacuation. In London alone, an estimated 541 high-rise building projects are planned for the next few years. A typical project, such as the £400 million '100 Bishopsgate' building, will have a peak of around 1,500 workers on site, and a cumulative workforce estimated at 12,000. The total number of workers exposed to construction sites in London during the lifetime of these 541 construction projects could easily exceed three million people.

AIMS:

The overall aim of the project is to improve the safety of construction site workers during on-site emergency evacuation, through the development of a unique evidence base characterising, for the first time, the actual performance and behaviour of construction workers during emergency evacuation. Combining this information with computer simulation will inform the development of more reliable evacuation procedures, improving the work environment through better preparation for, and management of, on-site emergency evacuation, and advancing the safety of construction workers.

METHODOLOGY:

The project consisted of four full-scale evacuation trials of two different high-rise buildings at two stages of construction, and five walking speed experiments. In total, 1,078 participants were involved in the nine trials, generating a data-set of around 2,200 data points, and information from 61 worker questionnaires. Analysis of this data produced generalised distributions for response times, walking speeds, stair speeds and ladder speeds, which were used to calibrate and validate the buildingEXODUS evacuation model. The validated model was then used to run 1,900 simulations exploring the impact on evacuation efficiency of changes to occupant response time, replacing formwork ladders with temporary stairs, and the use of hoists for evacuation.

RESULTS:

31 key findings from this analysis were produced:

- **questionnaire analysis –** eight key findings
- **generalised response time (RT) analysis relating to the formworks –** five key findings
- **generalised RT analysis relating to the main building –** three key findings
- **generalised climbing/walking speeds on ladders, temporary stairs and floor surfaces –** four key findings
- **validation analysis –** four key findings
- **use of the validated evacuation model to explore improvements in evacuation performance –** seven key findings.

CONCLUSIONS:

The project has developed a unique evidence base characterising, for the first time, the actual performance and behaviour of construction workers during emergency evacuation. It consists of (i) response times for workers in the main building and the formworks, as measured from the sounding of the alarm in the main building, (ii) worker walking speeds on different types of surfaces, such as concrete, decking and decking with rebar, and (iii) worker ascent and descent speeds on temporary dogleg and parallel scaffold stairs and ladders. The data has been incorporated in the building evacuation simulation tool buildingEXODUS, providing it with a unique capability to simulate

evacuation from high-rise construction sites. The performance of the software has been validated using measured data collected from the trials. The validated software has been used to explore how evacuation procedures for high-rise construction sites can be improved, including the impact of reducing worker response times, replacing ladders with temporary scaffold stairs within the formworks, and using hoists to assist in evacuation.

Executive summary

BACKGROUND:

The soaring scale of high-rise building construction – the number of projects and the size of the buildings – is reflected in the number of workers exposed to these demanding construction environments, and the potential for large-scale evacuation. In London alone, an estimated 541 high-rise building projects are planned for the next few years. A typical project, such as the £400 million '100 Bishopsgate' building, will have a peak of around 1,500 workers on site, and a cumulative workforce estimated at 12,000. The total number of workers exposed to construction sites in London during the lifetime of these 541 construction projects could easily exceed three million people.

AIMS AND OBJECTIVES:

The overall aim of the project is to improve the safety of construction site workers during on-site emergency evacuation, through the development of a unique evidence base characterising, for the first time, the actual performance and behaviour of construction workers during emergency evacuation. Combining this information with computer simulation will inform the development of more reliable evacuation procedures, improving the work environment through better preparation for, and management of, on-site emergency evacuation, and advancing the safety of construction workers.

The project has six key objectives:

- **Objective 1**: Develop an understanding of how construction site workers perceive the risk associated with working on high-rise construction sites
- **Objective 2**: Develop an understanding of the level of construction worker knowledge of evacuation procedures on construction sites
- **Objective 3**: Collect human performance data characterising the evacuation behaviour of construction workers, including response times and movement rates
- **Objective 4**: Provide evacuation data that could be used to validate evacuation models, specific to construction sites
- **Objective 5**: Through the use of evacuation modelling, utilising data collected in this project, demonstrate how evacuation procedures for construction sites can be optimised
- **Objective 6**: Through the better understanding of construction worker evacuation behaviour, and the optimisation of evacuation procedures, provide improved certainty of the outcome of evacuation situations, enabling a safer and more efficient response from emergency services.

METHODOLOGY:

To achieve these objectives, four full-scale evacuation trials and five walking speed experiments were conducted. In total 1,078 participants were involved in the nine trials, generating a data-set of around 2,200 data points, extracted from 3 GB of video data and information from 61 worker questionnaires. The data-set includes:

- the evacuation of 926 participants
- the measurement of 926 exit times
- the measurement of 270 response times
- walking experiments, involving 152 participants
- the measurement of 545 walking speeds over four different types of surfaces
- the measurement of 126 stair ascent/descent speeds on two different types of stairs
- the measurement of 59 ladder ascent/descent speeds
- the measurement of 203 interpersonal distances on temporary stairs.

The analysis of the collected data was used to produce generalised distributions for response times, walking speeds, stair speeds and ladder speeds. Combined, this information was used to calibrate the buildingEXODUS evacuation model and to provide a validation data-set. This data, and analysis associated with the data, addresses project Objectives 1–4.

The buildingEXODUS model was calibrated using the various worker performance data collected in the trials. Through running some 200 simulations, the calibrated software's suitability for simulating high-rise construction site evacuations was assessed to be acceptable using the high-rise evacuation validation data-set. Using the validated software, some 19 variations of high-rise construction site evacuation models were developed and used to run 1,900 simulations exploring the impact on evacuation efficiency of changes to occupant response time, replacing formwork ladders with temporary stairs, and the use of hoists for evacuation. The analysis of the data associated with the various simulations addresses project Objective 5 and, taken collectively, the data, knowledge and insight gained through this project addresses project Objective 6.

RESULTS:

The table below represents a high-level summary of the overall evacuation results from the four full-scale unannounced evacuation trials. The average response times for workers in the formworks varied from 29 s to 58 s while the average response time for workers in the main building varied from 62 s to 76 s. Total evacuation times varied from 9 m 14 s to 20 m 47 s depending on height of construction and number of workers, with exit flows varying from 0.08 p/s to 0.32 p/s. The low exit flow in Trial 2 was due to the majority of workers (30 of the 43) being located in the formworks, resulting in a few workers exiting early (those located low down in the main part of the building) while the majority exited later. Ignoring this value, the exit flows achieved in the trials where the workers are distributed throughout the building varied from 0.25 p/s to 0.32 p/s, with a weighted mean exit flow of 0.29 p/s.

Summary of key results from the four full-scale unannounced evacuation trials.

Trial and date	Location	Number of workers	Core level	Average formworks RT(s)	Average main building RT(s)	Total evacuation time (s)	Average exit flow (p/s)
Trial 1 14/02/17	100 BG	184	19	29	76	766 (12 m 46 s)	0.25
Trial 2 28/02/17	22 BG	43*	13^{X}	56	-	554 (9 m 14 s)	0.08
Trial 3 04/10/17	100 BG	308	38	-	62	1,098 (18 m 18 s)	0.29
Trial 4 16/11/17	22 BG	388	32^{X}	58^{+}	75	1,247 (20 m 47 s)	0.32

*: Excludes 3 workers from the South Core, ^{X}: North Core, $^{+}$: Excludes 6 supervisors.

The analysis of the collected experimental data and evacuation simulation results produced 31 key findings which are summarised as follows:

(1) Questionnaire analysis:

The questionnaires provided insight into worker knowledge of evacuation procedures and their perceptions of and response to the alarm. While only 7% of the participants of the four trials completed questionnaires, these represented 27% of the participants from the first two trials, and so provide statistically meaningful results, at least for these two trials.

The majority (62%) of respondents stated that they believed that the alarm sounding represented a real emergency. This is an important finding, as it suggests that the workers' response, and the data collected, may be representative of how they would react in a real emergency.

More than four-fifths (82%) of the participants knew that they were supposed to evacuate immediately on hearing the alarm, but only half (49%) reported that their first action upon hearing the alarm was to start to do so. However, while four-fifths (80%) of participants claimed they were prompted by the alarm, and did not require staff intervention to commence their evacuation, the video evidence suggests that many of the workers delayed the start of their evacuation. Furthermore, it suggests that at least 43% of the workers required staff intervention, a finding that highlights the need for, and importance of, assertive supervisors.

One possible explanation for workers not reacting as required by the procedures is that they may not be clear what is meant by 'evacuate immediately'. One way to address this problem is through enhanced training and/or greater enforcement of the policy by supervisors.

A potentially related finding is that workers perceived that employers find it more important than they do to complete their tasks prior to evacuating. This suggests that they may also be receiving mixed messages about the importance of immediate evacuation, and that improvements in local safety culture may be desirable.

In terms of risk perception, another important finding is that construction site workers not only have an appetite for risk comparable with the average person, but also perceive that they are in a safe environment while on their construction site. These results are somewhat surprising, given that construction sites are inherently hazardous environments. While the high level of perceived safety on Multiplex sites is a credit to the safety culture developed by the company, if workers are not also aware of, and alert to, the inherent dangers of a construction site, there is the risk of complacency in their response to potentially hazardous situations. One way to tackle potential complacency is through training that develops an understanding of how quickly an emergency situation can deteriorate, and reinforces the messages that 'every second counts' and 'immediately' means disengaging from pre-alarm activities as soon as an alarm is sounded.

Finally, while a third of participants (33%) stated that they knew the exit route, a fifth (21%) stated that they looked for emergency exit signage to assist in their evacuation. The high proportion of workers who relied on exit signage highlights the importance of having up-to-date and prominent emergency exit signage on site.

(2) and (3) Generalised response time (RT) distributions:
An important finding is that workers located within the formworks respond to the alarm differently to those in the main building: they tend to react quicker, and their RT is defined by a normal distribution, while the RT distribution for workers in the main building is defined by the typical lognormal distribution. This observation is supported by data from three different unannounced full-scale evacuation trials conducted on two different high-rise construction sites. As a result, two RT distributions are required to define the response behaviour of workers on high-rise construction sites. Furthermore, RTs in the main building could be as long as almost 6 minutes while the longest RTs in the formworks were longer than 2 minutes. The very long RTs found in the main building were normally the result of isolated workers or workers who had to make their pre-alarm activity safe prior to evacuating.

An unexpected finding is that the RT distribution for workers in the formworks and the main building does not appear to be impacted by the height of construction, at least for formworks located at up to

Level 33 (34 levels), and main building up to Level 38 (39 levels). As a result, it is possible to define generalised RT distributions for use in high-rise construction sites, at least up to 39 levels high. Further work is required to determine if this finding remains valid for higher construction sites.

Furthermore, for workers within the formworks, the nature of the work/phase of construction appears to influence response times. Average response times for those involved in high-priority work (such as fitting rebar just prior to a concrete pour) was approximately twice as long as for those involved in low-priority work (such as dismantling the formworks following a concrete pour).

It was noted that for workers in the main building, almost half (41%) react to the alarm in an appropriate manner, rapidly disengaging (in less than 40 s) and starting their evacuation movement phase without undertaking many (at most one task) preparation activities. Nevertheless, almost a third (32%) of the population require more than 60 s to disengage from their pre-alarm activities. Once disengaged, the population as a whole undertake an average of 2.2 tasks, but almost a quarter (23%) undertake four or more tasks. The long time to disengage, and the large number of tasks undertaken once disengaged, explains some of the long response times noted in the trials.

In contrast, the average time for supervisors within the formworks engaged in high-priority activities (prior to a concrete pour) to disengage from their pre-alarm activities on sounding of the fire alarm is 5.9 s. This extremely rapid disengagement is an example of the performance of well-trained and highly motivated staff.

Three generalised RT distributions have been defined: two (HPFW (high-priority formworks) and LPFW (low-priority formworks)) represent the response behaviour of workers in the formworks, and one represents the response behaviours of workers in the main building (MB). It is recommended that the HPFW is used for safety analysis that is general or associated with regulatory compliance, as it represents the longest response times observed. The LPFW distribution can be used to explore the impact of an evacuation at other times during the construction phase. The MB distribution represents the response time distribution for workers involved in a variety of activities, such as fitting rebar, glazing and MEP (mechanical, electrical and plumbing), and includes those working at height and isolated workers, within heights of construction up to 38 floors.

For the HPFW, the response times vary from 4.8 s to 133.2 s with a mean of 57.1 s (based on 60 data points from two trials in two buildings) while for the LPFW, the response times vary from 0.2 s to 50.7 s with a mean of 28.9 s (based on 20 response times from one trial). In contrast, the response time distribution for the MB varies from 0.9 s to 340.2 s with a mean of 71.3 s (based on 157 data points from three trials in two buildings).

It is important to note that the RT distribution data-sets do not include workers involved in concrete pours, or workers in high tower cranes. It is suggested that these workers are likely to contribute to the tail of the RT distribution, possibly extending the tail to longer response times, or increasing the frequency of those workers with longer response times.

HPFW RT distribution for the formworks:

$$\boldsymbol{f(t) = \frac{1}{28.554\sqrt{2\pi}} \exp\left[-\frac{(t - 57.08)^2}{2 * 28.554^2}\right]}$$

Where t (response time) is between 0 and 133 s. This can be used for formworks located at up to Level 33 (34 levels).

LPFW RT distribution for the formworks:

$$f(t) = \frac{1}{16.408\sqrt{2\pi}} \exp\left[-\frac{(t\ - 28.9)^2}{2 * 16.408^2}\right]$$

Where t is between 0 and 51 s. This can be used for formworks located at up to Level 33 (34 levels).

MB RT distribution for the main building:

$$f(t) = \frac{1}{t0.938\sqrt{2\pi}} \exp\left[-\frac{(\ln t - 3.908)^2}{2 * 0.938^2}\right]$$

Where t is between 0 and 350 s. This can be used for main buildings up to Level 38 (39 levels).

(4) Generalised walking speeds on ladders, temporary stairs and floor surfaces:
It has generally been assumed that the nature of the construction site floor surface does not influence the speed at which workers can walk. Furthermore, while it has been accepted that the ascent/descent speed of workers on ladders will be slower than that on stairs, the size of the reduction has not been quantified. Similarly, it is generally assumed that ascent/descent speeds of workers on temporary scaffold stairs are identical to that of normal stairs. These assumptions are critical when making estimates of how long it may take to evacuate a construction site. This project, for the first time, has quantified the walking performance of construction site workers on floor surfaces typically found on construction sites and the ascent/descent speeds on temporary stairs and ladders, and in the process uncovered a number of important and useful results.

Generalised walking speeds for workers ascending and descending on ladders and temporary scaffold stairs have been determined. The average ascent speed of workers on temporary scaffold dogleg stairs and standard building stairs are very similar while the average descent speed is 84% of the corresponding building stair speed. The device achieving the next fastest performance in both ascent and descent is the parallel stair, with the ladder producing the slowest speeds. The average descent speed on parallel stairs is 74% of the stair descent speed for normal building stairs, and the average ascent speed is 79% of the normal stair ascent speed. For ladders, the average descent and ascent speeds are 52% and 67% of the corresponding normal building stair speeds. The slower ascent/descent speeds on these vertical access devices is an important consideration when determining means of escape from high-rise construction sites as they will not only increase the time required by individuals to evacuate, they will also reduce the flow capacity of the vertical means of escape.

The most frequent interpersonal spacing between workers on a single flight of the temporary scaffold dogleg stairs, when three or more workers occupy the flight, was two treads, and the most common number of people that was accommodated on the flight was three. The observed spacing is significantly different to that found on regular building stairs, which is typically one tread between occupants in high-density situations. The reason for the apparent reluctance of users of temporary stairs to pack more densely is not clear. It may simply be a result of the smaller tread depth found on the temporary stair, and/or the perceived fragility of the stair. The higher interpersonal spacing on the temporary stair will have a negative impact on the flow capability of the stair, decreasing it compared to a permanent stair of similar width.

Generalised walking speeds on flat surfaces consisting of concrete, decking and decking with rebar were determined, with the magnitude of the walking speed being affected by the nature of the surface, the speed on concrete being the greatest. A set of walking speed reduction factors has been developed, based on the speed on concrete. The reduction factors relate to the experience of the worker, where inexperienced workers have a greater reduction in walking speed than experienced workers. On average, walking speeds on concrete are fastest, followed by across decking, rebar and then along decking. For inexperienced workers, walking speeds along decking can be as little as 68% of the walking speed on a concrete surface. It is recommended that the inexperienced reduction factors are used when dealing with a safety analysis that is general, or associated with regulatory compliance, as this represents the greatest reduction in walking speeds over each of the surfaces and is therefore more conservative. The slower than expected walking speeds on various floor surfaces that are typically found on construction sites is an important consideration when determining maximum permissible travel distances and the time required by individuals to escape from high-rise construction sites.

(5) Validation analysis:
A validation data-set has been defined, describing the evacuation of a high-rise construction site consisting of 227 workers distributed over 34 levels. While there are several uncertainties concerning some initial conditions for the data-set, it can be used to assess the performance of evacuation simulation software. The average exit curve, produced by 100 repeat simulations of the buildingEXODUS evacuation simulation software, produces a reasonable approximation of the validation data-set. On average, the total evacuation time is over-predicted by 4%, while the time for half the population to exit the building is under-predicted by 22%. The average time to clear the jumpform is under-predicted by 15%. Given the uncertainties in the validation data-set, this is considered an acceptable level of agreement. Furthermore, an objective measure of acceptable agreement between model prediction and experimental data has been specified using a performance metric defined using the ERD (Euclidean Relative Difference), EPC (Euclidean Projection Coefficient) and SC (Secant Coefficient). This takes into consideration the uncertainties in the data-set and the performance of the buildingEXODUS software. Finally, a validation framework has been defined to carry out independent validation assessments using the validation data-set presented in this report.

(6) Use of the validated evacuation model to explore improvements in evacuation performance:
The validated evacuation simulation software and data-sets were used to explore potential improvements to evacuation procedures on high-rise construction sites, arising from reduced worker response times, replacing ladders with temporary stairs within the formworks, and using hoists for evacuation. In each case, the target building consisted of 525 workers, including 125 workers located in the formworks. The main findings are:

- Decreasing the response times of workers has the potential to decrease the overall construction site evacuation time; however, the effectiveness of this approach in improving evacuation efficiency is dependent on a number of interacting factors including the magnitude of the reduction in response times, the number of workers affected, the height of construction and the nature of the available vertical means of escape. Two different reductions in response time were explored, one in which response time of the slowest responders in the main building was targeted and another in which response time of all workers was targeted:

    - Decreasing the maximum response time for workers in the ***main building*** by 42% and producing a 27% reduction in average response times results in a 26% or 12% decrease in the average total evacuation time for workers in the main building for construction sites of 22 levels and 42 levels respectively. These results suggest that substantial improvements in total evacuation time can be achieved by reducing the response times of the slowest responders. However, the improvement gains in total evacuation time achieved by reducing the average and maximum response times of the main building population diminish with increasing height of construction. It is also noted that the overall evacuation time for the entire building is unaffected. This is due to the 125 workers located in the formworks, who are the last to evacuate, not being affected by the reduction in response times.

- Reducing the response time for ***all workers*** by 50% results in a 33% decrease in the average total evacuation time for workers in the main building for high-rise construction sites of up to 22 levels. While achieving a 50% reduction in everyone's response time may be difficult to achieve in practice, it can result in reducing evacuation times for the main building population by a third. However, the evacuation time for the entire building, which is driven by the evacuation time for workers located in the formworks, is essentially unaffected. This is due to the congestion experienced by workers in the formworks attempting to use the sole means of escape: a single ladder.

- The overall evacuation time for the high-rise construction site is governed by the time for the 125 workers located in the formworks to clear them. This, in turn, is impacted by the severe congestion that occurs at the entrance point to the only exit from the formworks: a single ladder. Replacing the ladders in the formworks with temporary scaffold dogleg stairs reduces the time required to clear the formworks by 17% (67 s). As the last people to leave the building are from the formworks, this also decreases the overall building evacuation time. For a high-rise construction of up to 22 levels, the overall building evacuation time is decreased by 8% (51 s), while for high-rise construction of up to 42 levels, the total building evacuation time is decreased by 6% (55 s). While replacing the single ladder exit route with a single temporary stair results in an appreciable reduction in the time required to clear the formworks, considerable congestion remains at the head of the temporary stair. Thus, the time required to clear the formworks could be decreased further if the flow capacity of the exit route from the formworks could be increased by, for example, the addition of a second exit route, or if the single-lane stair were replaced with a dual-lane stair.

- The use of hoists for evacuation is extremely complex and depends on a number of factors, including number of available hoists (eight in the case examined), hoist dispatch strategy (each hoist ferrying occupants between a targeted floor (every other floor) and ground), hoist performance (fast/slow), hoist capacity (40/30), building height (22/42 levels) and proportion of population that uses the hoist for evacuation (0%, 50% and 100%). It is thus difficult to generalise to accommodate all possible or likely situations.

  The most efficient evacuation was achieved using fast high-capacity hoists. Using these hoists, it was noted that:
  - for both low (22 levels) and high (42 levels) high-rise construction, the use of hoists – whether by 100% or 50% of the population – resulted in at least a 19% improvement in total evacuation time, over the stairs-only case
  - overall evacuation times could be reduced by 30%, compared to stairs only, if 100% of the occupants used the hoists
  - evacuation efficiency increases with construction height when 100% of the population use hoists
  - if 50% of the population use the hoists, evacuation times increase compared to the 100% hoist usage, but this is still at least 19% quicker than using the stairs only.

  In the worst case, the use of slower low-capacity hoists resulted in the poorest performance, almost always causing significantly longer evacuation times, compared with the use of stairs only. For high high-rise construction sites (up to 42 levels), if 100% of the occupants used slower low-capacity hoists for evacuation, this could increase evacuation times by 80%, compared with the stairs-only case. If 50% of the population used hoists, evacuation times were increased by 16%.

CONCLUSIONS:

The project has developed a unique evidence base characterising, for the first time, the actual performance and behaviour of construction workers during emergency evacuation. It consists of (i) response times for workers in the main building and the formworks, as measured from the sounding of the alarm in the main building, (ii) worker walking speeds on different types of surfaces, such as concrete, decking and decking with rebar, and (iii) worker ascent and descent speeds on temporary dogleg and parallel scaffold stairs and ladders. The data has been incorporated in the building evacuation simulation tool buildingEXODUS, providing it with a unique capability to simulate evacuation from high-rise construction sites. The performance of the software has been validated using measured data collected from the trials. The validated software has been used to explore how evacuation procedures for high-rise construction sites can be improved, including the impact of reducing worker response times, replacing ladders with temporary scaffold stairs within the formworks and using hoists to assist in evacuation.

1 Introduction and project overview

1.1 Introduction

The construction industry is one of the major industrial sectors in the UK. It includes three industry groups, construction of buildings, civil engineering and specialised construction activities, which are further divided into nine classes and 28 subclasses. In February 2018 there were an estimated 2.73 million workers employed in the UK construction industry [1], representing some 8.4% of the UK workforce (which in January 2019 was approximately 32.5 million workers [2]).

The soaring scale of high-rise building construction – the number of projects and the size of the buildings – is reflected in the number of workers exposed to these demanding construction environments, and the potential for large-scale evacuation. In London alone, an estimated 541 high-rise building projects are planned for the next few years [3]. A typical project, such as the £400 million '100 Bishopsgate' building, will have a peak of around 1,500 workers on site, and a cumulative workforce estimated at 12,000 [4]. Based on these figures, the total number of workers exposed to construction sites in London during the lifetime of these 541 construction projects could easily exceed three million people.

Statistics suggest that there are several thousand construction site fires annually in the UK [5], while in the USA, there are an estimated 4,800 construction site fires per year (based on statistics between 1996 and 1998) [6]. However, thankfully, fires on construction sites have not resulted in large loss of life or serious injury in the UK in recent years. Nevertheless, according to the UK government and the Health and Safety Executive (HSE) statistics [7], in the construction industry on average annually there are 39 fatal injuries to workers (for 2013/14–2017/2018) and 58,000 non-fatal injuries to workers (for 2015/2016–2017/2018). The statistics also reveal the main cause of death and injury on construction sites. The five main kinds of fatal accident for construction workers, which account for 86% of the total worker fatalities, are:

- fall from height
- trapped by something collapsing
- struck by object, struck by moving vehicle
- contact with electricity.

In addition, the four main kinds of non-fatal injuries (those that account for 10% or more of injuries) to construction workers are:

- slips, trips or falls on same level
- injured while handling, lifting or carrying
- falls from a height
- struck by moving, including flying/falling, object.

In 2017/2018 there were 38 construction industry fatalities among the construction industry workforce, making this the industrial sector with the largest loss of life in the UK. However, when considered by the number of fatalities per 100,000 employed, the construction sector is the fourth most dangerous industry (see Table 1). Nevertheless, it has an average fatality rate almost four times that of the land-based industries in general.

Table 1. Average annual fatality rate over five-year period and fatality rate for 2017/18.

Sector	Average annual fatality rate per 100,000^{X}	Fatality rate per 100,000 2017/2018^{X}
Fishing industry	55.34*	64.0**
Agriculture	8.20	8.44
Waste and recycling	7.22	10.26
Construction	1.77	1.64
All industry^{+}	0.45	0.45

^{X}: based on data from 2013/14–2017/18, excluding fishing industry [7]; *: based on data for the fishing industry from 2013–2017 [8]; **: based on report in [9]; $^{+}$: excluding fishing industry.

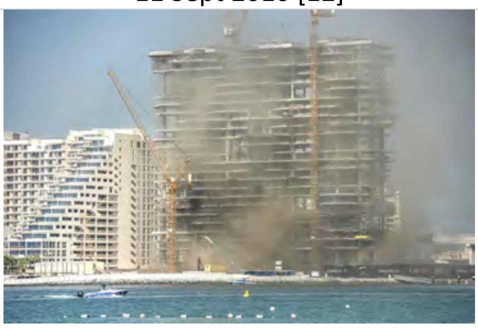
While fatal fires on UK construction sites are rare, there have been major fires on construction sites in the UK and around the world. Recent examples from the UK and around the world are depicted in Figure 1.

The Broadgate Phase 8 fire, London, UK
23 June 1990 [10]

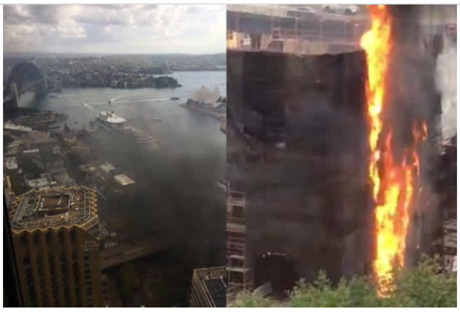
The Glasgow School of Art's Mackintosh building fire, Glasgow, UK
16 June 2018 [11]

The Basingstoke construction site fire, Basingstoke, Hampshire, UK,
11 Sept 2010 [12]

The Fountain Views tower fire, Dubai, UAE,
02 April 2017 [13]



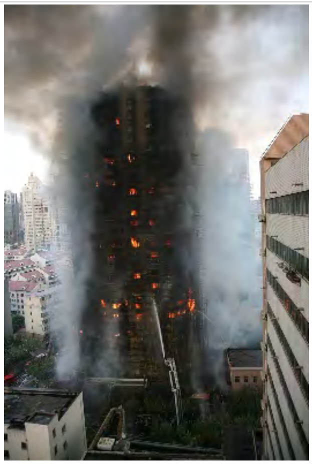
Construction building fire in Palm Jumeirah, UAE, 26 Oct 2017 [14]



Construction site fire at Circular Quay, Sydney, Australia
13 Feb 2018 [15]

Under construction apartment building fire in Oakland, USA
7 July 2017 [16]

The Shanghai World Financial Centre fire, Shanghai, China
14 August 2007 [17]



The 11·15 Shanghai high-rise flats fire, Shanghai, China
15 Nov 2010 [18]

Figure 1. Examples of major fires on construction sites in the UK and around the world.

While fire does not account for a major source of deaths or injuries on UK construction sites, given the high frequency of fires and the number of workers on construction sites, there is nevertheless a significant risk to the health and safety of workers if an emergency evacuation caused by fire or other on-site emergency is required. Other types of emergency situation that may require the rapid evacuation of a construction site include severe unexpected weather, earthquake and partial building collapse [19]. Furthermore, it is also necessary to ensure that evacuation plans are sufficiently robust so that they can deal with unexpected events – a recent example is the evacuation of a high-rise construction site due to a collision of a helicopter with a construction site crane in the fog [20]. It is therefore essential that large-scale construction sites have robust plans to ensure a safe and timely emergency evacuation – for whatever reason – should one be required.

1.2 Study aims

The overall aim of the project is to improve the safety of construction site workers during on-site emergency evacuations. This will be achieved through the development of a unique evidence base characterising, for the first time, the actual performance and behaviour of construction workers during emergency evacuation. This information combined with computer simulation will be used to inform the development of more reliable evacuation procedures. These developments will contribute to improving the work environment through better preparation for, and better management of, on-site emergency evacuation and thereby improving the safety of construction workers.

1.3 The issues

Construction sites in general, particularly high-rise construction sites, pose a significant fire risk due to the nature of the work (e.g. hot work), the storage and use of flammable materials and the open nature of the construction site (providing little or no compartmentation protection and allowing wind to impact fire development and smoke movement). Furthermore, the height of construction and the number of workers on site can make vertical evacuation challenging, especially as, in the event of a fire, the vertical evacuation routes are unlikely to offer a safe refuge, as they do within the completed building. In addition, during most of the construction phase, the automatic fire detection and protection measures intended to operate in the completed building are not yet in place or fully operational. Compounding these fire safety issues are the inherent challenges the construction environment poses to safe evacuation, including:

- **Changing connectivity of the physical environment:**
  During construction, the very layout of the building, its interconnectivity and traversibility of paths, is constantly changing, on occasion several times a day (see Figure 2). As a result, evacuation plans and procedures must be kept under constant review and adapt to the changing physical environment. As evacuation plans change to adapt to different phases of construction, these plans must also be conveyed to, and understood by, the construction workers.

Figure 2. Constantly changing connectivity on construction sites.

- **Worker familiarity with the layout:**
  The workforce makeup is constantly changing. Some workers may be on site for perhaps only a few days and so may not be very familiar with the layout, while other workers may need to visit the site during different construction phases and so will not be familiar with the current environment or, worse, may be confused by the changed layout. This highlights the need to have evacuation routes clearly signed and visible, ensuring that the signage keeps up with the changing nature of the environment (see Figure 3).

Figure 3. Emergency exit sign about to be obscured by work on the construction site.

- **Number of workers on site:**
  Evacuation plans must be able to adapt to the numbers of workers on site. The number of workers on site is constantly changing: the population may involve tens of people one day and several hundred the next. Evacuation routes suitable for 20 people may not be appropriate for 200 (see Figure 4).

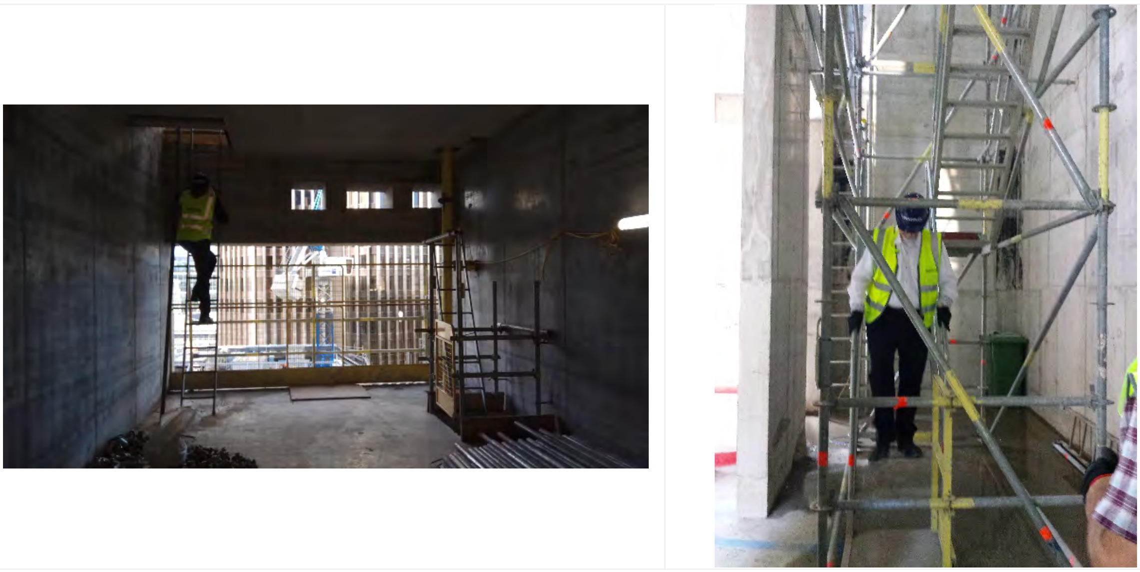


Figure 4. Evacuation routes suitable for a few workers may not be appropriate for hundreds.

- **Number of different nationalities on site:**
  The construction site population is likely to be made up of many different nationalities [21–23] and so language may impact communications and, more subtly, cultural differences may influence worker attitude to evacuation, evacuation procedures and evacuation performance.

- **Challenge of alerting workers:**
  The manner in which the population is alerted to the need to evacuate may also vary during different construction phases due to the availability of power for alarm systems, the level of noise on site and the nature of ear protection worn by workers (see Figure 5).

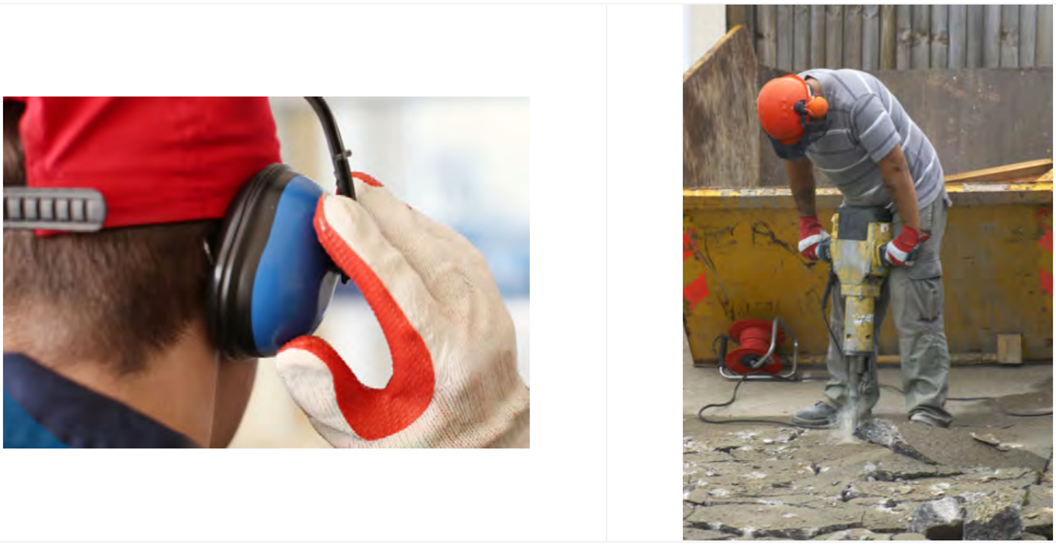


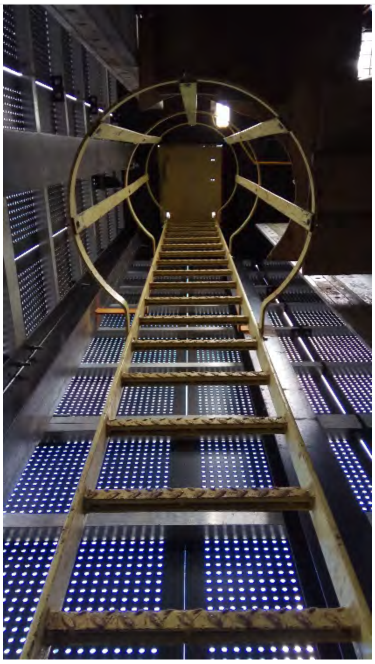
Figure 5. Loud noises and the use of ear protectors may make it difficult for workers to hear the emergency alarm.

- **Delayed response to alarm:**
  Depending on the nature of the activity that the construction worker is engaged in, even if they can hear the alarm, they may not be able to readily abandon their pre-alarm activity and engage in the evacuation activity. They may need to spend time to make safe a pre-alarm activity, thus delaying their response to the alarm (see Figure 6). Thus, unlike in a standard building evacuation, response times (time between sounding of the alarm and the time at which the person engages in evacuation movement activities) for construction workers may not follow the typical 'lognormal' distribution commonly found in every other evacuation environment [24–26] and may vary widely.

Figure 6. Nature of work may not allow workers to rapidly respond to evacuation alarm.

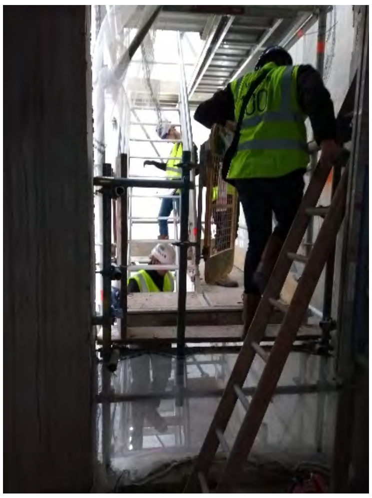
- **Varying nature of the terrain:**
  In most evacuation situations we take the surface over which we walk for granted. It is assumed to be a familiar floor surface or a familiar stair configuration and so has little or no 'special' impact on our ability to evacuate. However, on construction sites the very surface over which workers must travel is not necessarily what may be considered 'typical'. Evacuation routes could involve decking or decking with rebar and the stairs may be temporary stairs which are narrower, steeper and may have less head clearance, or instead of stairs there may be ladders (see Figure 7). All of these different types of terrain are likely to have an impact on evacuation performance, even if the person is well experienced in dealing with these types of surfaces.

(a) Temporary scaffold stairs.



(b) Vertical ladder.

(c) Steel grid.



(d) Temporary ladder and stairs.

(e) Decking.

(f) Decking with rebar.

Figure 7. Typical surfaces and vertical connections found on construction sites.

Regular evacuation drills may be used by construction site managers to prepare their workforce for an emergency and as a means to better understand some of these issues and to optimise evacuation plans and procedures. However, these are seldom unannounced (drill in which the workforce and the supervisors have no knowledge of the timing of the drill) evacuation drills. Thus, workers and/or supervisors are usually aware that a drill will take place on a given day and in some cases at a given time. Thus, workers and supervisors can prepare for the drill and may even pre-empt the evacuation. This fails to test construction site workers' knowledge of the evacuation process, how they respond to an alarm, the effectiveness of the procedures in place and the effectiveness of the training processes employed.

To address these challenges, health and safety (HS) authorities impose regulations and guidelines to ensure safety of workers on construction sites. In the UK for example, The Regulatory Reform (Fire Safety) Order 2005 [42] and the Management of Health, Safety and Welfare Regulations 1999 [43] require an assessment-based approach to controlling risks associated with fire and other emergencies. General guidance on evacuation safety for construction sites comes under the remit of health and safety (HS) with specific guidance contained within the Health and Safety Executive (HSE) publication HSG168 [5].

Furthermore, evacuation simulation tools [27–31] could also be used to assist construction site HS managers develop, plan and test evacuation procedures used during the various construction phases. Evacuation simulation tools are commonly used in assessing evacuation capabilities of large complex buildings and in developing evacuation plans during the design phase. Over the years a considerable database of human performance and behaviour has been established to calibrate these models so that they can be used reliably [32, 33]. Furthermore, validation data-sets have been developed to assess how accurately evacuation models can predict evacuation performance thereby providing regulators, designers and building operators with confidence in the results produced using these models [32, 34–36].

However, for regulations, guidelines and simulation models to be meaningful, they must be based on a reliable evidence base describing the performance and behaviour of construction workers during emergency evacuation situations. For example, how quickly do workers react to the evacuation alarm, how quickly can they walk over the various surface types, how is wayfinding impacted by on-site conditions, etc.? This data is essential to frame meaningful regulations and guidance and to calibrate evacuation models thereby enabling them to be used for construction site applications. Furthermore, to improve the confidence in applying evacuation models to construction site applications, it is necessary to have a reliable validation data-set representative of construction sites.

1.4 UK regulations and guidance

Several high-profile fires in the UK have highlighted the serious financial losses and devastating consequence of fires on construction sites. These include the Broadgate Phase 8 fire in 1990 [10], the London Underwriting Centre, Minster Court fire in 1991 [37–39], the Basingstoke construction site fire in 2010 [40] and the Glasgow School of Art's Mackintosh building fire in 2018 [41], which resulted in a total loss valued at several hundred million pounds. In response to the fire risk at construction sites, a number of legal requirements and guidance documents have been produced to address fire safety and evacuation on construction sites. These include:

- The Regulatory Reform (Fire Safety) Order 2005 (FSO) [42]
- The Management of Health and Safety at Work Regulations 1999 [43]
- The Construction (Design and Management) Regulations 2015 (CDM 2015) [44]
- *Fire prevention on construction sites*. Joint Code of Practice 9th edition, 2015 [45]

- *Managing health and safety in construction*. Construction (Design and Management) Regulations 2015. Guidance on regulations L153 [46]
- *Health and safety in construction* HSG150 [47]
- *Fire safety in construction work* HSG168 [5]
- *Workplace health, safety and welfare*. Workplace (Health, Safety and Welfare) Regulations 1992. Approved code of practice and guidance L24 [48]
- *CIBSE Guide E: Fire Safety Engineering* 2010 [49].

It is noted that general guidance on evacuation safety for construction sites comes under the remit of health and safety (HS) with specific guidance contained within the Health and Safety Executive (HSE) publication HSG168 [5]. The following are highlights in the legal requirements and guidance documents which are related to evacuation performance in an emergency.

- The Regulatory Reform (Fire Safety) Order 2005 (FSO) [42]
    - **Regulation 14**. **Emergency routes and exits** (page 11)
      – "…it must be possible for persons to evacuate the premises as quickly and as safely as possible."
    - **Regulation 15**. **Procedures for serious and imminent danger and for danger areas** (page 12)
      – "…the procedures … must enable the persons concerned (if necessary by taking appropriate steps **in the absence of guidance or instruction** and in the light of their knowledge and the technical means at their disposal) to **stop work and immediately proceed** to a place of safety in the event of their being exposed to serious, imminent and unavoidable danger."

- The Construction (Design and Management) Regulations 2015 (CDM 2015) [44]
    - **Regulation 30**. **Emergency procedures** (page 16)
      – "(1) …**suitable and sufficient arrangements** for dealing with any foreseeable emergency must be made and, where necessary, implemented, and those arrangements must include procedures for any necessary evacuation of the site or any part of it."
      – "(2) In making arrangements under paragraph (1), account must be taken of —
        (a) the type of work for which the construction site is being used;
        (b) the characteristics and size of the construction site and the number and location of places of work on that site;
        (c) the work equipment being used;
        (d) the number of persons likely to be present on the site at any one time;…"
      – "(3) Where arrangements are made under paragraph (1), suitable and sufficient steps must be taken to ensure that—
        (a) each person to whom the arrangements extend is familiar with those arrangements; and
        (b) the arrangements are tested by being put into effect at suitable intervals."

    - **Regulation 31**. **Emergency routes and exits** (page 16)
      – "(1) … a **sufficient number** of **suitable emergency routes and exits** must be provided to enable any person to reach a place of safety quickly in the event of danger."
      – "(2) The matters in regulation 30(2) must be taken into account when making provision under paragraph (1)."
      – "(5) Each emergency route or exit must be **indicated by suitable signs**."

- *Health and safety in construction* HSG150 (third edition) [47]
    - **Emergency procedure and planning for an emergency**. 79–82 (pages 16, 17) – "…escape routes need to be **wide enough** to allow everyone to get through doorways or down stairs **easily** without them becoming overcrowded."

- *Fire safety in construction work* HSG168 [5]
    - **Travel distance:** 190–196 (pages 35, 36)
      – "…It is important **not to over-estimate how far people can travel** before they are adversely affected by fire. Appropriate distances and the time taken to reach safety will depend on various factors …"
      – "…distances are for guidance only and **may vary according to the risk assessment**."

Table 2. Recommended maximum travel distances to a place of safety [5].

		Fire hazard		
		Lower	**Normal**	**Higher**
Enclosed structures	**Alternative**	60 m	45 m	25 m
	Dead-end	18 m	18 m	12 m
Semi-open structures	**Alternative**	200 m	100 m	60 m
	Dead-end	25 m	18 m	12 m

    - **Stairways, external escape stairs and ladders**: 197–201, 206, 207 (pages 36–38)
      – "It is especially important to ensure that the stairways and ladders are located or protected so that any fire will not prevent people using them."
      – "If … it is not reasonable to provide or maintain an internal protected stairway, external temporary escape stairs may be provided instead. **Adequate stairways can be constructed from scaffolding** …"
    - **Escape route sizing**: 208–211 (pages 38, 39)
      – "While stairways etc may be adequate for normal entry and exit, it is important **not to overestimate their capacity** in an emergency…"
      – "… if during the construction work the number of people present is greater than the design maximum of the finished building, additional escape routes, or increased sizing of these, might well be necessary."
      – "…the **speed at which people can escape via ladders is much slower**. Ladders may be suitable for simple projects and for small numbers of able-bodied, trained staff."
    - **Compartmentation**: 243–251 (pages 45, 46)
      – "For escape routes, compartmentation can assist evacuation where areas are large and they should provide a degree of protection above or below floor/roof level."
    - **Emergency procedures and action plan for fire**: 261–266 (pages 47, 48)
      – "Plan emergency procedures before the work begins and put general precautions in place to support these from the start of the work."
      – "If simultaneous evacuation is needed, make sure the escape routes are of **sufficient capacity** to achieve this."
      – "…If there are personnel on site who do not speak English, it is imperative that any **instructions or procedures are made clear** and they understand what is needed in the event of an emergency."

1.5 Ambiguity and gaps in UK regulations and guidance

Based on examining the highlights in Section 1.4, the following questions are raised which are related to the ambiguity and gaps in regulations and guidance.

- Given the ambiguity of the regulations and lack of detailed specification of important parameters, e.g. the frequent use of terms such as **"suitable and sufficient", or "not to overestimate their capacity", or "adequate stairways", or "wide enough"**, how is it possible to determine if the requirements specified by regulations and guidance have been satisfied?
- On hearing an emergency alarm, do workers **"stop work and immediately proceed"** to a place of safety? How long do they take to respond to an alarm? What factors influence their response times? Are response times affected by height of construction or type of work?
- What is the difference in **escape route capacity in normal use and during an emergency** and what, if any, will be its impact on evacuation performance?
- Do the guidelines (e.g. **maximum travel distance, escape route sizing**) provide sufficient safety measures? How is this impacted by the number of people on site?
- What is the impact of different types of surface on travel speed? How does this affect **maximum travel distance, escape route sizing and evacuation time**?
- Is it reasonable to assume or require that workers will **"stop work and immediately proceed to a place of safety"**? How is this to be achieved? How long do construction workers typically take to respond to an evacuation alarm? What is the impact of worker delayed response on evacuation performance? How much can be gained by improving worker response to the alarm? How likely are workers to respond in an appropriate manner without **guidance or instruction**?
- How **familiar** are workers with the evacuation procedures? Is it **reasonable** to assume that workers know how to respond appropriately to the alarm? How do we assess worker understanding of the evacuation procedures? Apart from performing a full-scale evacuation drill, how can we reliably test the appropriateness of the evacuation procedures?
- While the **"speed at which people can escape via ladders is much slower"**, what is the travel speed of workers on ladders? Furthermore, while **"ladders may be suitable for simple projects and for small numbers of able-bodied, trained staff"**, how many staff are appropriate to be served by ladders and in what circumstances? When part of an evacuation route includes ladders, what impact do they have on evacuation performance?
- While it is claimed that **"Adequate stairways can be constructed from scaffolding"** what does adequate mean, what type of scaffolding stairs is implied, are all forms of scaffolding stairs equivalent? What is the speed of workers on different types of scaffolding stairs? What is the impact of scaffolding stairs on evacuation performance?
- How sensitive is evacuation performance to obstructions on evacuation routes? How can we assess the impact of the changing nature of exit route availability on evacuation performance?
- Can fire smoke compromise means of escape such as temporary stairs or hoists? Has wind direction and speed been considered?
- Can construction site hoists make a useful contribution to the evacuation of construction sites (see [17] as an example)? If so, under what conditions? Is there a critical height above which they become effective?

This study intends to address many of these gaps in the regulations and guidelines through the establishment of an evidence base describing construction site worker evacuation performance and in the development of a calibrated evacuation modelling tool capable of simulating evacuation from high-rise construction sites.

1.6 Study objectives

The project has six key objectives.

Objective 1: Develop an understanding of how construction site workers perceive the risk associated with working on high-rise construction sites. The results addressing this objective are discussed in Section 4.5.

Objective 2: Develop an understanding of the level of construction worker knowledge of evacuation procedures on construction sites. The results addressing this objective are discussed in Section 4.5.

Objective 3: Collect human performance data characterising the evacuation behaviour of construction workers, including response times and movement rates. The results addressing this objective are discussed in Section 4.

Objective 4: Provide evacuation data that could be used to validate evacuation models specific to construction sites. The results addressing this objective are discussed in Section 5.

Objective 5: Through the use of evacuation modelling utilising data collected in this project, demonstrate how evacuation procedures for construction sites can be optimised. The results addressing this objective are discussed in Section 6.

Objective 6: Through the better understanding of construction worker evacuation behaviour and the optimisation of evacuation procedures, provide improved certainty of the outcome of evacuation situations, enabling a more efficient and safer response from emergency services. The results addressing this objective are presented in Section 7.

1.7 The study

To meet the core objectives, the study was split into five distinct tasks.

Task 1 – project planning and preparation.
A key component of the project was the collection of the evidence base. Two types of trial were conducted. The first consisted of four full-scale unannounced evacuation trials of high-rise construction sites. These trials would provide data for the response times and for the validation data-sets. Two sites were selected, and each was evacuated twice while at different heights of construction. The second type of trial consisted of five experiments to collect walking speed data. The data was collected through the use of video cameras and participant questionnaires. Once the trials were planned, ethical approval to conduct the trials was obtained. Only once ethical approval was obtained could the trials begin. This task, which contributes to Objectives 1 to 4, has been successfully completed and is described in Section 3 of this report.

Task 2 – data collection.
Each site was prepared for the trials, which involved setting up the video equipment. For the full-scale trials this had to be done the night before the trials were conducted so as not to alert the workers. Each of the four full-scale evacuation trials and five walking speed experiments were successfully conducted, generating a vast amount of raw data. This task, which contributes to Objectives 1 to 4, has been successfully completed and is described in Section 3 of this report.

Task 3 – data analysis.
All the collected data had to be analysed, which involved first extracting the raw data from the video footage and the questionnaires. Once the raw data was extracted, the data was analysed to better understand how workers perceive risk on the construction site, to create an evidence base describing how workers perform during evacuation from high-rise construction sites and to establish a validation

data-set for evacuation from high-rise construction sites. This task has been successfully completed and is described in Section 4 of this report, addressing the requirements of Objectives 1 to 3.

Task 4 – validation analysis.
The human performance data is used to calibrate the buildingEXODUS evacuation modelling software. For this software to be able to make reliable predictions of human behaviour during evacuation it requires reliable human performance data describing parameters such as response times, travel speeds and wayfinding choices. Other software calibration is required to ensure that features that currently function for completed buildings, such as lifts, can accommodate on-site variations such as the use of hoists for evacuation. The validation data-set is then used to assess the performance of the calibrated buildingEXODUS evacuation model in performing evacuation simulations of construction sites by comparing its predictions to the observed evacuations. This task has been successfully completed and is described in Section 5 of this report, addressing the requirements of Objective 4.

Task 5 – using the validated evacuation model to demonstrate potential improvements to construction site evacuation.
To demonstrate the potential use of the validated software and data-sets, several potential improvements to evacuation procedures on high-rise construction sites are systematically examined and changes in evacuation performance quantified. The potential enhancements investigated are: improving the response time of workers, replacing ladders with temporary stairs in the formwork and use of hoists for evacuation. This task has been successfully completed and is described in Section 6 of this report, addressing the requirements of Objective 5.

Taken collectively, the completion of Tasks 1 to 5 addresses the requirements of Objective 6 with the key findings summarised in Section 7.

2 Literature reviews and background information

Presented in this section is a brief overview of the literature describing evacuation behaviour within buildings (Section 2.1), the literature associated with evacuation of construction sites (Section 2.2) and an overview of the key components of high-rise building sites that are relevant to this project (Section 2.3).

2.1 Evacuation behaviour

The evacuation process is generally considered to comprise two broad phases: the response phase and evacuation movement phase [25, 50–54] (see Figure 8). These are described in this section along with the data that is used to characterise these phases in building evacuation.

2.1.1 Evacuation response phase

The evacuation process commences sometime after the incident (e.g. the start of the fire) begins. The evacuation process can only start once the occupants begin to receive the first incident cues such as the sounding of the fire alarm, notification by staff/firefighters or environment cues such as the smell of smoke, observation of flames, etc. There is an inevitable lag between the start of the incident and when the first incident cues are detectable by the at-risk population and hence the start of the evacuation process (see Figure 8).

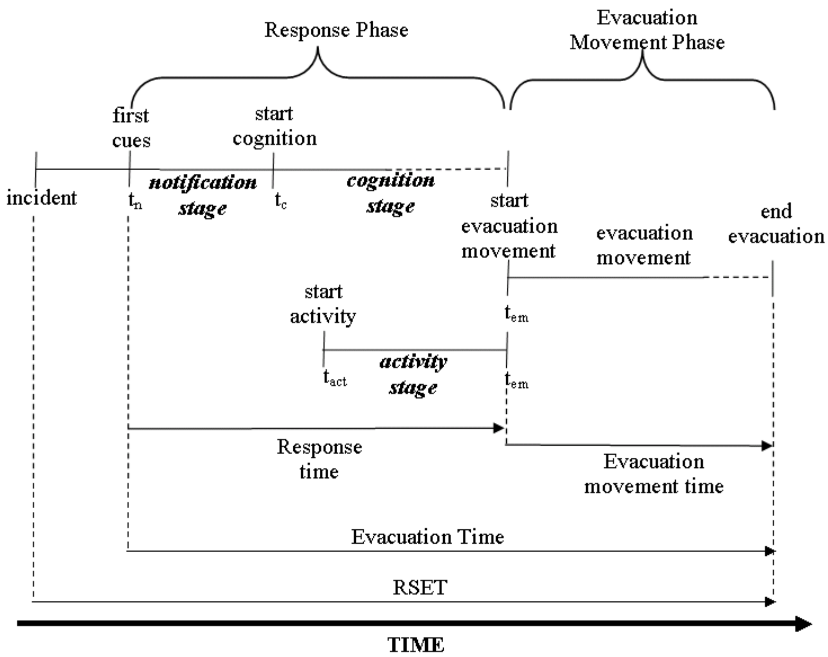


Figure 8: Framework for describing evacuation behaviour [25, 50, 51].

During the response phase, occupants receive a number of early incident cues (notification stage) and after some time they respond to these cues and eventually disengage from their pre-incident activities (notification time). However, in most cases, prior to starting decisive evacuation movement they decide (cognition stage) to undertake a variety of activities such as packing belongings, searching for others, investigating the cues, seeking confirmation from others, etc. and undertake these activities (activity stage) prior to starting decisive evacuation movement [25, 50, 51]. The evacuation movement phase cannot commence until the response phase has been completed. All of this serves to postpone the start of decisive evacuation movement. The duration of the response phase is often called the response time, sometimes also confusingly referred to as pre-evacuation time or pre-movement time

[25, 50–60]. The response time is therefore the time interval between the sounding of the alarm (or receipt of other first fire cues) and the point at which the occupant begins to make decisive movement towards an exit or stair or place of safety.

It is only at the start of the evacuation movement phase that the occupant begins their purposeful movement to an exit or stair or place of safety. The response time is thus dependent on a number of separate but distinct behaviours: the time required to disengage from the pre-alarm activities (notification time) and the time required to contemplate (cognition time) and complete all of the action and information tasks (activity time) required prior to starting decisive movement to the exit or place of safety.

The required safe egress time (RSET) for a particular incident scenario is measured from the start of the incident (not the alarm) to the time for the last at-risk person to exit or reach a place of safety and so is dependent on the detection time, response time and evacuation movement time [25, 50–54]. In most cases, where there is a functioning automated fire detection system, the detection time can be quite small and so the key times become the response time and the evacuation movement time. In some situations, e.g. those involving sleeping occupants, the response time may be longer than the evacuation movement time. Thus the duration of the response time is a critical factor in determining the length of the RSET and hence the success or failure of an evacuation. However, in situations where there is no automated detection system and associated global alarm system, the detection time may become a large (perhaps even the dominant) component of the RSET, significantly delaying the start of the response phase and thereby reducing the time available for safe evacuation movement.

As already described, the way individuals within an at-risk population react to an evacuation alarm is dependent on a number of factors such as the population size and spatial distribution, population demographics, interpersonal relationships, prior evacuation experience, training, building familiarity, alarm type, nature of cues received and nature of pre-incident activities [25, 50–55]. These will in turn impact the notification time and/or the number and type of action and information tasks undertaken and hence the overall activity time. As a result, each person within the at-risk population will have a unique response time, creating a distribution in response times for the population. The nature of the enclosure (e.g. building) will influence many of these factors, so that a given population exposed to a particular type of alarm may display different response phase behaviours (influencing notification time and the number and type of action and information tasks undertaken and hence the activity time) if they are in, for example, an office building, railway station, shopping mall or residential building [25, 50, 51, 54–60]. However, irrespective of the type of enclosure, the distribution of response times typically follows a lognormal distribution as depicted in Figure 9 [25, 50, 51, 54–60]. Each specific scenario (consisting of enclosure type, nature of population, nature of detection/alarm system, nature of hazard, time of day, etc.) will have a particular lognormal response time distribution which is distinguished by its mean and standard deviation.

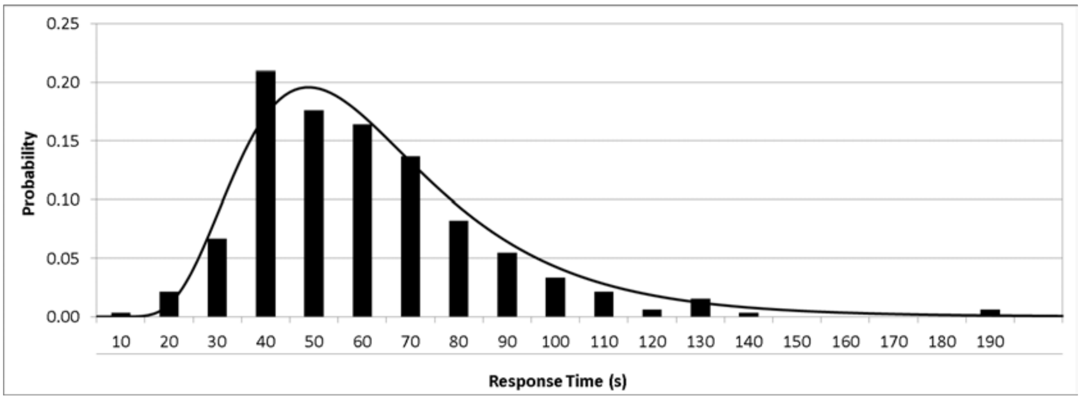


Figure 9. Response time frequency distribution for a theatre [25].

2.1.2 Evacuation movement phase

After the evacuation response phase, occupants begin the evacuation movement phase. Depending on the nature of the structure, this can involve a combination of horizontal and vertical movement. Horizontal walking speeds of individuals depend on several factors including age, gender, nature of footwear, slope of inclination and crowd density [61]. Data suggests that unimpeded walking speeds on flat terrain for adults peak at about 20 years of age, reaching a maximum of about 1.6 m/s for males and 1.4 m/s for females [62]. As the surrounding crowd density increases, walking speeds tend to decrease, reaching a stagger at around 4 people/m^2 [61].

A number of studies have analysed stair walking speeds and explored the influence of physical characteristics on walking speed. Perhaps the best known and most widely used stair movement data was generated by Fruin who measured free flow stair walking speeds of 700 males and females of various ages, both descending and ascending stairs using two different stairs, one with a slope of 31.9° and the other with a slope of 26.5° [61]. This data shows that average ascending speeds are always slower than average descending speeds and that males always travel faster than females on average. For example, males aged 30–50 years have average speeds of 0.88 m/s and 0.63 m/s descending and ascending respectively, while females in the same age range have average speeds of 0.67 m/s and 0.59 m/s [61, 65].

Other data often quoted concerning stair walking speeds are derived from observations of high-rise building evacuation drills [64]. These clearly demonstrate that stair walking speeds are dependent on the population density on the stairs, with a mean speed of 0.48 m/s in optimal flow conditions and 0.20 m/s in crush conditions [64].

Stair walking speeds have also been estimated from past real incidents such as the 9/11 World Trade Center disaster [67–69]. The UK BDAG study [67] first reported lower than expected walk speeds derived from their sample of survivor accounts published in the public domain. Their relatively small sample of useable data suggested a mean stair descent walk speed of 0.24 m/s. The later NIST report [68], based on a larger sample of first-hand survivor accounts, suggested an even lower mean stair descent walk speed of 0.20 m/s. The UK HEED study, also based on first-person accounts of 30 occupants of the North Tower, suggests an average adjusted stair speed of 0.29 m/s [69].

The calculated stair walk speeds were adjusted for periods of time that the occupants remained stationary due to congestion. Furthermore, the HEED study suggests that occupants with stair speeds less than the average speed encountered high levels of congestion for at least 60% of their stair descent. It appears reasonable to suggest that the lower than expected stair speeds in the WTC appear to be affected predominately by high levels of congestion experienced on the stairs for significant periods of time.

A summary of the historic stair data is presented in Table 3 [76]. As can be seen, most previous research has focused on full-scale experiments or accident investigation data and focused on issues to do with walking speed as a function of crowd density.

Stair width constrains the nature of the ascending and descending movement on the stair**.** The stair width restricts the number of people that can comfortably walk side by side (occupying the same stair tread) on the stair. While walking on stairs, people tend to keep at least a single tread gap between themselves and the person directly in front. When in motion, this provides sufficient space for a person to move forward without bumping into the person directly in front of them.

Stair width also constrains stair flow [77]. Flow is defined as the rate of people passing over a defined line in a given period of time (people/second). The flow is a function of the average speed of movement of the population (m/s), the crowd density of the population passing over the defined line (people/m^2) and the passage width (m) as described in Equation 1.

$$\textbf{Flow (p/s) = speed (m/s) x density (p/m}^2\textbf{) x passage width (m)} \quad \textbf{(1)}$$

However, the speed is also a function of the flow density – the speed remains constant at its nominal value at low densities (less than about 0.5 people/m^2), but as the density increases, the speed begins to decrease, dropping to a crawling pace (at about 4 people/m^2) before reaching zero at very high densities (5–7 people/m^2). As a result, as the flow density increases, the flow increases until an optimal density is reached where the flow reaches a maximum; after this point, as the density further increases the flow tends to decrease, eventually coming to a standstill at a maximum density. A measure of flow independent of the width of the passage is the unit flow, which is defined as the flow per metre passage width (people/m/s). The unit flow for a passage type tends to be constant irrespective of its width for passage widths greater than about 1.0 m [77].

As the width of the passage decreases, the maximum achievable flow tends to decrease while the unit flow remains approximately constant. For a 1.3 m wide stair, the optimal density is about 1.9 people/m^2 resulting in a maximum flow of about 1.6 people/s and a unit flow of 1.2 people/m/s [54]. For a typical 1.1 m wide stair, a rough rule of thumb is that the optimal flow is about 1 person/s or about 60 people/min.

Table 3. Occupant stair walking speeds derived from various experiments [76].

Year	Mean speed$^{*,+}$ (m/s)	Comments	Source
1971	1.01, 0.67 0.76, 0.64 0.88, 0.63 0.67, 0.59 0.67, 0.51 0.60, 0.49	Male under 30 years, down and up Female under 30 years, down and up Male 30–50 years, down and up Female 30–50 years, down and up Male over 50 years, down and up Female over 50 years, down and up Data is averaged over two different stair slopes (31.9° and 26.5°) and represents unimpeded walk speeds. US data-set	Galea et al [65] derived from Fruin [61]
1969	0.58±0.15	Data derived from observations of stairs in actual use. Russian data-set.	Predtechenskii and Milinskii [63]
1971	0.48 0.20	Optimal flow conditions Crush conditions	Pauls [64], derived from Fruin [61]
2001	0.20	Median value, 9/11 WTC Towers Incident data, US data-set	Averill et al. [68]
2001	0.29	WTC North Tower Incident data, US data-set	Galea et al. [69]
2004	1.19, 1.15 0.91, 0.88	Mixed age group, average age 35 years, down and up Mixed age group, average age 71 years, down and up Mean unimpeded stair walk speeds averaged over two different stair slopes (30.5° and 35.0°). Single flight of stairs, 13 men and 20 women. UK data-set	Fujiyama and Tyler [71] based on analysis in this paper
2007	0.64	Data derived from evacuation trial in a 7-floor building involving 281 people. Finnish data-set	Hostikka et al [70]

2008	0.52 (0.27, 1.55) 0.84 (0.14, 1.54) 0.90 (0.58, 1.44)	Mean unimpeded ascent (min, max), 73 people, 35° stair Mean unimpeded ascent (min, max), 10 people, 22.2° stair Mean unimpeded descent (min, max), 6 people, 22.2° stair German data-set.	Kretz et al. [66] based on analysis in this paper
2008	0.42, 0.32 0.36, 0.30	Adult male, down and up Adult female, down and up Short stairs, vertical travel speeds. Singaporean data-set	Yeo et al. [73]
2010	0.48±0.16	Derived from 8 full-building evacuation drills in buildings from 6 to 62 floors high. US data-set	Peacock et al. [72]
2012	0.28	Mean unimpeded vertical travel speed, 101 floors, 6 subjects aged 21 to 62 years with average of 34 years	Ma et al. [75]
	0.59	Mean unimpeded speed determined using riser-tread ratio of 0.54.	Ma et al. [75] based on analysis in this paper
	0.62	Mean speed, 177 participants mainly young, 17 floors Chinese data-set	Ma et al. [75]
2012	0.81	8-storey building, evacuation experiment. Chinese data-set	Fang et al. [74]

* Unless stated otherwise, stair speed is measured along the stair slope.
+ Unless stated otherwise, stair speed refers to descent speed.

2.2 Review of literature relating to construction site evacuation

As already highlighted (see Section 1.3), there are a number of issues that influence evacuation performance that are unique to construction sites, making evacuation of construction sites one of the most challenging evacuation scenarios conceivable. However, globally over the past 50 years, very little, if any evacuation research has focused on issues unique to construction sites. For the most part, the evacuation and construction site safety literature is silent on research with a focus on identifying and understanding the nature of the behaviour of construction workers during emergency evacuation situations and with developing an evidence base quantifying the performance of construction site workers during evacuation.

One of the few studies with a specific focus on evacuation behaviour of workers on construction sites concerns evacuation from tunnels under construction undertaken by Lund University in 2010 [78]. This work concerned fires and evacuation from tunnels under construction. The researchers identified some of the challenges faced by tunnel construction workers, including a constantly changing environment making wayfinding difficult, reduced visibility due to the presence of fire smoke, noise making it difficult to communicate and the nature of the surfaces making physical movement difficult such as the slope of the tunnel, slippery surfaces due to water and the presence of rails (for the tunnel boring machine (TBM)). To address some of these issues they undertook an evacuation drill of a tunnel under construction involving 25 workers in a TBM and used the data to run some simple evacuation models to assess the impact of various scenarios on the time to evacuate the TBM and the tunnel. The data collected from the trial is very limited and only applicable to very specific tunnel applications involving TBM. However, the work is important as it highlights some of the unique issues associated with the evacuation of construction sites and the general lack of an evidence base to support both regulation and modelling.

Gangolells et al [79] developed a risk-based analysis technique in 2010 that attempted to identify the risk level associated with various construction designs. The approach uses a risk ranking approach to compare overall safety risk on construction sites. However, the approach does not take into consideration the detailed nature of the construction site layout or how workers may respond to this.

In 2012 Hisham et al [80] proposed developing and using an agent-based evacuation model based on the social forces concept to simulate the evacuation of construction sites. Using such a model, they argue, would enable improvements in planning of construction site evacuation by taking into consideration the changing nature of the layout of the construction site. However, apart from the changing nature of the geometry of the construction site, they fail to identify many of the challenging issues associated with construction site evacuation and how these would be addressed by such a model. Indeed, they even claim that their model would assume that all the workers on the construction site would be totally familiar with the (changing) nature of the construction site. They also fail to identify the need for an evidence base to calibrate evacuation models or how the evacuation model would be verified or validated.

In 2016 [81] and more recently in 2019 [82], Zhang et al developed an agent-based model, not to simulate evacuation behaviour, but to represent the interaction between workers and supervisors to explore the impact this may have on influencing worker emergent safety-related behaviour. Their approach models different managerial scenarios and attempts to determine the impact this may have on worker behaviour related to safety aspects, e.g. the impact of different safety inspection strategies and different safety training strategies on worker behaviour. Agent behaviours are based on data collected from worker surveys conducted on nine different railway construction sites in China and on observations of worker behaviour. The surveys were designed to measure the impact of management behaviour on worker behaviour. While this work had a focus on safety, it did not include issues associated with evacuation.

Abune'meh et al [83] developed a spatial layout model (using the space syntax approach) in 2016 to identify the optimal layout for a construction site, i.e. the best location for each of the key facilities (e.g. storage facilities, staff offices, canteen, cranes, hoist) typically found on construction sites in order to minimise the risk associated with potential incidents occurring. The approach is based on the hazards generated by potential incidents (e.g. fire, explosion), the vulnerability of targets (i.e. other facilities) and a hazard attenuation function (e.g. assume linear decay of hazard with distance). By developing a risk map for the site, site managers can manually plan evacuation routes that take workers through routes with acceptable risk. However, the approach does not automatically identify optimal evacuation paths or how these may be impacted by the developing hazard or take into consideration the workers or how the layout may impact the behaviour and performance of the workers during an evacuation.

In 2016, Leite et al [84] published a paper identifying the modelling, simulation and visualisation grand challenges facing the construction industry. The analysis was based on a workshop attended by 27 academic and eight industrial experts involved with information technology in the US construction industry. A list consisting of the 17 top-ranked grand challenges was prepared and an expert survey was developed to investigate the relative importance of the identified challenges and to collect associated factors regarding current practices and future directions. The questionnaire was then distributed to 100 academic (architecture and design, architecture and civil engineering, construction management and laboratory directors) and industrial practitioners (BIM managers, project managers, business and development managers, applied technology directors, etc.) involved in information technology within the US construction industry.

While evacuation of construction sites was not explicitly cited in the survey responses, safety of construction sites was referenced throughout. Furthermore, the incorporation of human behaviour into agent-based simulation models was identified as the fourth most challenging grand challenge for the construction industry with verification and validation of simulation models being the third most challenging grand challenge. The survey further found that the experts agreed that most of the challenges associated with verification and validation could be addressed through the collection of data from construction sites.

While very little research has been directed towards the specific challenges associated with the evacuation of construction sites, it is clear that there is an interest and need for the establishment of an evidence base describing evacuation behaviour of construction site workers and an appetite for the use of agent-based models capable of reliably simulating evacuation from construction sites.

2.3 Construction of high-rise buildings

For the purposes of this project, it is important to identify several components of high-rise buildings during their construction. For high-rise construction sites, the 'core' of the building is fabricated first. The core is much like the spine of the building and will eventually house all of the vertical access, such as elevators and staircases, as well as supply utilities to all floors (such as water and electricity).

The core is built using a climbing formwork (see Figure 10), such as a slipform or a jumpform. The formwork generally contains shutters which act as a mould into which concrete is poured. A slipform is continuously (and slowly) moving, whereas in the case of a jumpform, the core will be built a level at a time and then the form will 'jump' to the top ready for the construction of the next level.

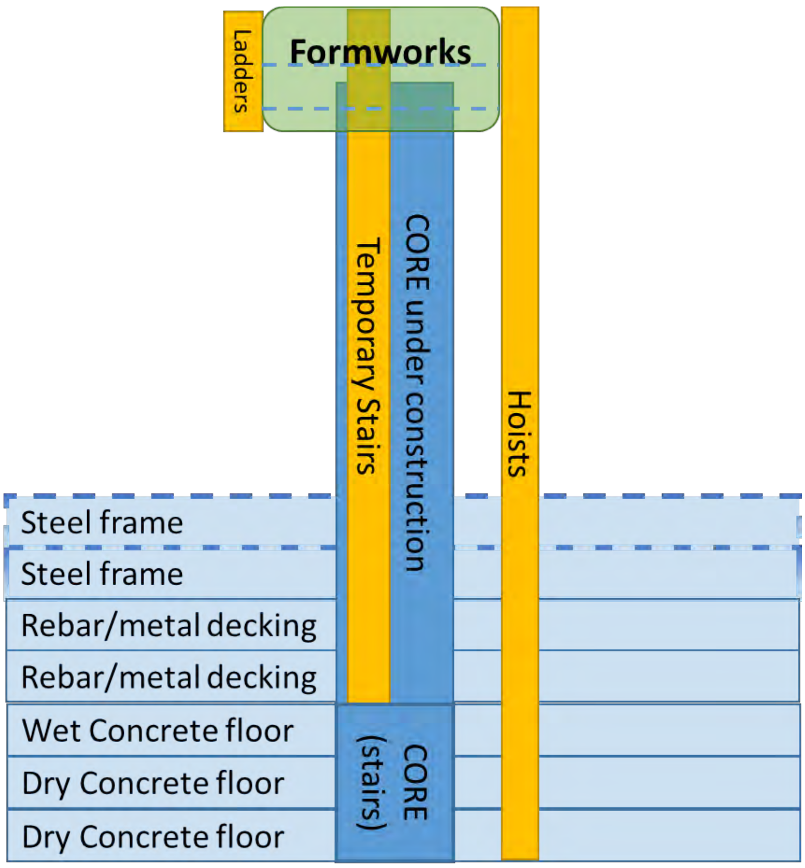


Figure 10. General make up of a high-rise construction site.

Once the concrete in the core has sufficiently cured, steel framework can be attached which defines the basic structure of the building floor layout. With the steel framework in place, metal decking is placed on top of the framework. Following this, rebar will be placed on top of the decking and then concrete will be poured to form the reinforced concrete floor as shown in Figure 10.

Depicted in Figure 11 is 22 Bishopsgate, one of the construction sites used in the project as it appeared on 13 September 2017. The key components relevant to this project are depicted; at this time the site had:

- seven completed floors
- eight partially completed floors: two levels of new/wet concrete, two levels of rebar, two levels of metal decking and two partial levels of steel frameworks
- the North Core extended up to Level 27
- the South Core extended up to Level 31
- each jumpform (North and South) being three decks above the highest completed core level, with the top deck being approximately a full level above the base deck.

Figure 11. Annotated image of 22 BG from 13 September 2017.

For the two construction sites used during this project, there were always two levels of steel framework, two levels of metal decking, two floors of rebar and two floors of wet concrete. Beneath these levels, the general work taking place consisted of such tasks as the installation of glazing/external facia, plant equipment and utilities. Within the formworks, generally there is very little free space (see Figure 12) and so ladders are used to enable workers to move from one deck to another deck within the formworks (see Figure 13). For reasons of safety, it is considered good practice to allow only one person on a ladder at a time. At the top of many of the ladders within the formworks is a hatch with an alarm attached to it to warn others that there is a worker climbing up the ladder and about to open the hatch.

Figure 12. Typical conditions within the formworks.

Figure 13. Two ladders connecting levels of the jumpform at 100 BG.

For the rest of the construction site, a combination of hoists, permanent stairs and temporary staircases are used to transport workers vertically between the various levels of the construction site. Hoists are essentially lifts which are used to carry a number of workers at any one time. Some hoists can also carry heavy items such as building materials and tools/machinery. Hoists are not generally used during an emergency situation (see Figure 14).

Permanent stairs are those that will be used in the final constructed building, which can be used by the workers once the concrete has sufficiently cured (see Figure 15a). However, in some parts of the core the stairs are incomplete and not able to be used (see Figure 15b), while in other parts of the core, the stairs do not exist at all. When there are no stairs or partially completed stairs available, temporary stairs are introduced. Temporary stairs are usually built within a scaffold tower and consist of metal steps. Once the building is completed or when the permanent stairs catch up with the temporary stairs, the temporary stairs are removed. Temporary stairs may be located within the stair shaft of the building (assuming there are no completed or partially completed stairs) or in empty lift shafts, or they may be located on the exterior of the building. During this study, two types of temporary stairs were identified: dogleg and parallel stairs. These are illustrated in Figure 16 with examples from the construction sites depicted in Figure 17.

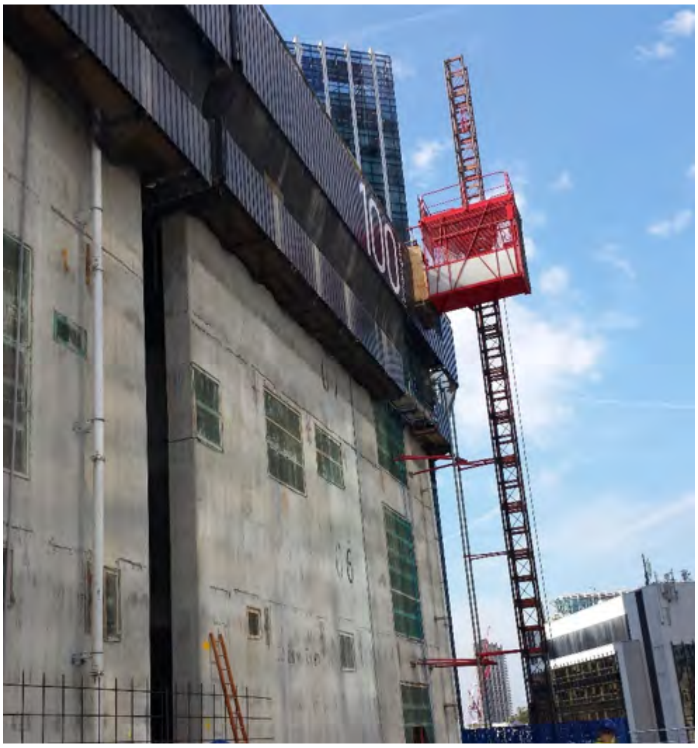
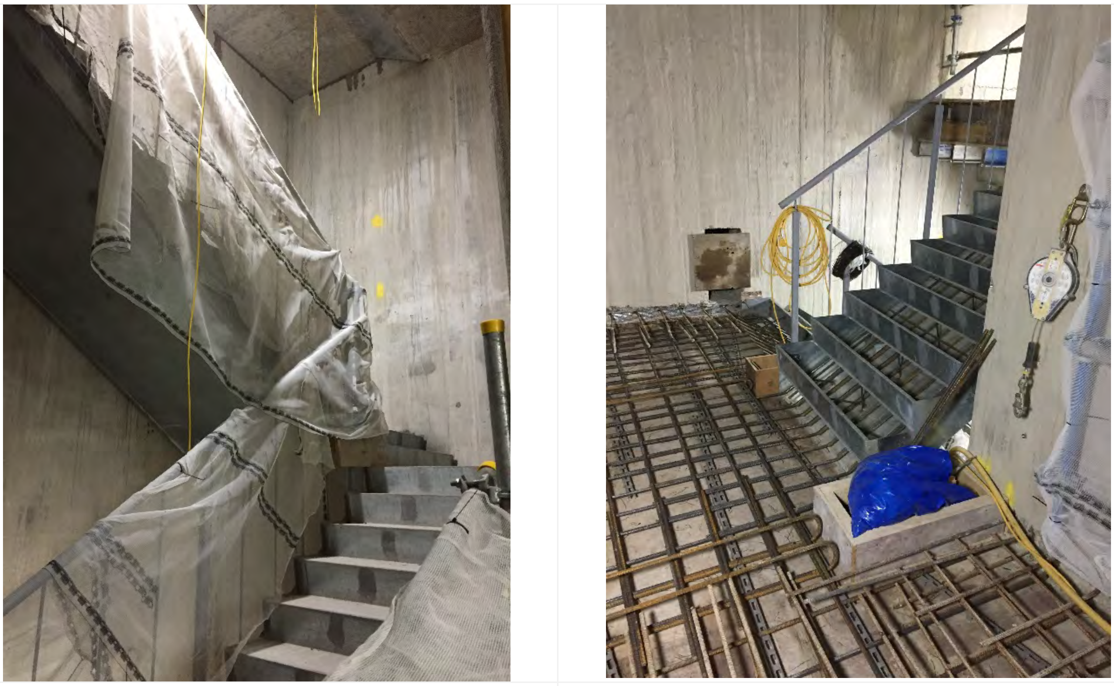
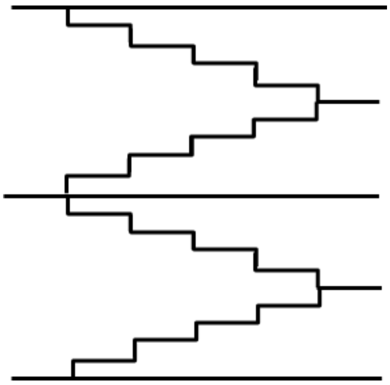


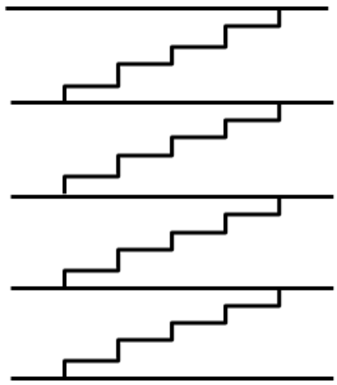
Figure 14. External hoist at 100 BG.



(a) Completed stair within building core.	(b) Partially completed stair in building core.

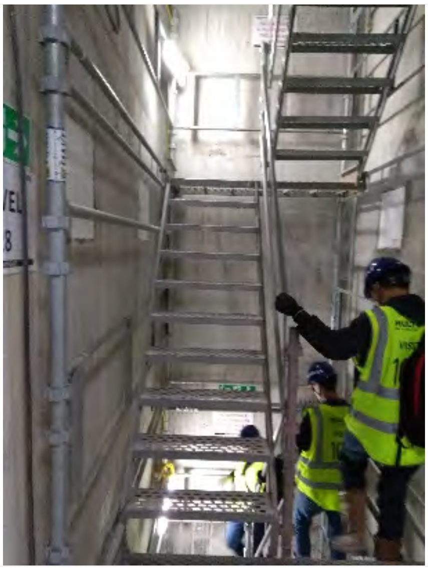
Figure 15. Completed and partially completed stairs within the building core (100 BG).





(a) Dogleg Stairs.	(b) Parallel Stairs.

Figure 16. Two types of temporary staircases.



(a) Temporary scaffold dogleg stairs (within a building core).	(b) Temporary scaffold parallel stairs (within a building core).

Figure 17. Temporary scaffold stairs within a building core arranged in dogleg and parallel arrangements.

3 Project methodology

This section describes the work undertaken to address project Tasks 1 and 2.

3.1 Introduction

As with most large experimental projects, not everything in this project went according to plan. The schedule for conducting the four full-scale evacuation trials experienced a number of setbacks due to various issues on the construction sites. This meant either that the site could not be evacuated due to a change in work schedules which meant that there would be insufficient workers on site in the required locations to make an evacuation trial meaningful or changes in work schedules that meant that essential work that could not be interrupted had been brought forward or brought back and clashed with the proposed evacuation trial. In addition, a serious illness meant that project director Prof Galea was not available for an extended period while he recovered. Furthermore, it became apparent during planning that not all the data required could be collected from the envisaged full-scale unannounced evacuation trials necessitating the development of an additional series of experiments to generate the necessary data. These additional experiments further delayed the completion of the project. The planning presented in this report takes these setbacks into consideration and does not report on the impact that each had on the progress of the project.

To achieve the objectives of the project the following data was collected from the various trials using different techniques.

- From the full-scale evacuation trials through the analysis of video data (see Section 3.2 to 3.4):
  - measure response times of workers engaged in a range of activities typically found on high-rise construction sites. This requires the capture of multiple people engaged in the same activities to develop an understanding of the range of response
  - measure overall evacuation time.

- From the full-scale evacuation trials through the analysis of questionnaire data (see Section 3.5):
  - identify the workers' perceived level of risk of danger on the construction site
  - measure the workers' knowledge of the evacuation procedures
  - measure worker understanding of evacuation routes.

- From the walking speed experiments through the analysis of video data (see Section 3.6):
  - measure travel speeds of workers over different types of surfaces e.g. metal decking or rebar
  - measure travel speeds on different types of temporary stairs.

3.2 General planning full-scale evacuation trials

3.2.1 Introduction

In principle, the general approach for running an unannounced full-building evacuation involves the following key steps:

- weeks before the trial, identify site-specific location for video cameras to capture the required movement and behaviour data
- weeks before the trial, ensure that data collection tools (video cameras, and questionnaires) are available
- on the day before the trial (a date agreed with senior management and only known to the trial team), ensure that data collection tools are prepared
- on the night before the trial, install video equipment after most workers have left the site

- on the morning of the trial, activate and synchronise the video cameras first thing in the morning before workers arrive on site
- at the specified time, agreed with senior management and only known to the trial team, activate the alarm
- on completion of the evacuation, distribute questionnaires
- on completion of the evacuation trial, collect completed questionnaires and video equipment.

Following the above general procedure, FSEG successfully completed a pilot trial in collaboration with Multiplex at their Aldgate Tower high-rise construction site in 2013. The trial demonstrated the feasibility of undertaking full-scale unannounced evacuation trials of high-rise construction sites. The experiences gained from the pilot study were used to refine the detailed procedures for this more comprehensive study.

In selecting the high-rise construction sites to be investigated in this project, the sites had to satisfy several project constraints. The two sites had to be located in central London so as not to impose significant logistical constraints on the project team. Each site had to be available during two different phases of construction to ensure that data would be collected at two different heights of construction. This was essential to ensure that the impact of height on evacuation behaviour could be taken into consideration. Furthermore, ideally the evacuation trials on both sites should take place when both sites were at similar heights of construction to ensure that there was some confidence in the repeatability and hence generality of the collected data. Finally, the dates and times for the trials had to coincide with there being a significant number of workers on site and during a period when there was no essential (unstoppable) work taking place such as concrete pours in the formwork (any time delay during a concrete pour could result in a weakness in the structure of the building and an expensive and time-consuming process to rectify).

The project team, in consultation with the project advisory board, identified two high-rise construction sites in central London that would be appropriate for the needs of the project. The two sites provided by Multiplex were 22 Bishopsgate (22 BG) and 100 Bishopsgate (100 BG), both of which are located in central London.

The 100 BG site, once completed, will be a 40-storey office block, standing at approximately 172 metres tall. Construction of 100 BG made use of a slipform to build the core of the building. As described in Section 2.3, this involves a continuously climbing formwork. The site, as of 14/02/17, is depicted in Figure 18a.

The 22 BG site, once completed, will be a 62-storey office block which, at the time of writing, is expecting to have the largest core in Europe. The core contains the lift shafts and main stairwells which will supply all the floors with vertical access as well as supplying utilities (water/electricity/air conditioning etc.) and the rising fire mains to all floors. The core is being built in two sections, the North Core and the South Core, with each core consisting of two lobby areas each. Each core is being built using a jumpform which, as described in Section 2.3, creates a level at a time and then 'jumps' to the top once the concrete has cured sufficiently to hold the weight of the formworks. At approximately 278 metres high, it is expected to be the tallest building in the City of London and second tallest in London (behind the Shard). The site, as of 13/09/17, is depicted in Figure 18b.

(a) 100 BG (photograph taken on 14/02/17). (b) 22 BG (photograph taken on 13/09/17).

Figure 18. The two high-rise construction sites used in the four evacuation trials.

Multiplex provided the University of Greenwich (UoG) with the required building plans (in the form of AutoCAD drawings) which needed to be updated on a regular basis following the progress of the construction. As plans were modified on site, they were emailed to the research team. In addition, Multiplex kept the research team informed as to the current state of construction, expected delays, estimations of the number of workers on site and the general tasks being performed or expected to be performed.

The research team also conducted several site visits to each site. These visits provided the research team with a good understanding of the layout of the construction sites, the types of work undertaken and the procedures followed by the workers, vital information for planning how to approach each trial. As a result, several types of site visit were required. The first were familiarisation visits allowing the research team to understand the layout of the site, the activities taking place on the site and an opportunity to visit the site management team, in particular the site team that would liaise with and facilitate the work. The second set of site visits were required to identify the regions which would be monitored during the trials and where video cameras would be mounted and assess the equipment that would be needed. Finally, the third set of site visits were undertaken the night before the trials to set up all the required equipment.

During these visits it soon became apparent that the workers could be located anywhere on a particular floor at the time of the evacuation. As a result, it would be extremely difficult (if not impossible) to accurately monitor the physical movement of sufficient workers over sufficient distance on the various types of floor surfaces to make accurate estimations of walking speeds.

Therefore, at an early stage in project planning, additional laboratory style experiments were proposed in order to obtain sufficient data regarding workers' travel speeds across the various floor surfaces. The floor surfaces were concrete, along metal decking, across metal decking and along/across metal decking with rebar. As these additional experiments were to be conducted it was also decided to collect travel speed data for workers travelling on the temporary scaffold stairs, of which there were two types: dogleg stairs and parallel stairs (see Section 2.3).

A total of four full-scale unannounced evacuation trials were planned: two trials at 100 BG and two trials at 22 BG. The second set of trials at each site were scheduled to take place a number of months after the first set at each site in order to ensure that the construction had moved on significantly in terms of the height of the building works. As already reported, there were a number of delays in performing the second round of trials, but all four trials were completed as shown in Table 4. In total some 926 workers would take part in these four unannounced full-building evacuation trials.

Table 4. Summary of conditions for each evacuation trial.

Trial and date	Location	Number of workers	Core level	Number of floors (in various stages of completion)
Trial 1 14/02/17	100 BG	184	19	12
Trial 2 28/02/17	22 BG	46	13	0
Trial 3 04/10/17	100 BG	308	38	33
Trial 4 16/11/17	22 BG	388	32	20

3.2.2 General planning timeline for the full-scale evacuation trials

As it was important that the workers did not witness the research team setting up the video camera equipment on site (thus informing them of the impending evacuation trial), the video cameras were set up the night before each trial, once almost all the workers had left the site. Each trial was scheduled for early morning when the workers would be back on site, at their work area and having recently started their tasks (thus minimising the delay in construction work due to the evacuation trial).

As part of the planning procedure, a general timeline was developed to ensure that each full-scale evacuation trial proceeded as planned and in a consistent manner.

- Two days before trial:
  - check and, if required, charge video camera batteries
  - clear all video camera memory (SD cards)
  - pack all required equipment (as listed in Section 3.4)
  - print questionnaires in appropriate languages for construction site and box them ready for transporting to construction site.

- Day before trial:
  - final equipment checks prior to leaving FSEG offices
  - FSEG team arrive at site office for induction, briefing and issuing of PPE (at approximately 17:00)
  - FSEG team enter the construction site and commence setup of cameras (at approximately 18:00)
  - FSEG team complete setup (approximately four hours) and leave site (at approximately 22:00).

- Day of trial:
  - FSEG team arrive on site (at 06:30)
  - FSEG team start turning on, recording and sync clocks on each video camera (at approximately 07:00).

- The trial:
  - building alarm sounded (at approximately 09:00)
  - jumpform alarm sounded approximately one minute later (for Trial 1 only)
  - evacuation over (at approximately 09:30)
  - FSEG team start distributing questionnaires (at 09:30)
  - FSEG team start taking down equipment (starting at approx. 09:35 and taking about three hours)
  - FSEG team pack up equipment (at approximately 12:00)
  - FSEG team complete collecting questionnaires (by approximately 13:00).

- Day following trial:
  - FSEG team download data from video cameras on to computers and recharge camera batteries
  - FSEG team create a data view file using statistical software and then input questionnaire responses into this data file ready for analysis
  - analysis of trial footage and questionnaire data commences.

3.3 Specific site details full-scale evacuation

In this section the details of the building at the time of the evacuation are described along with specific details of the trial plans.

3.3.1 Trial 1, 100 Bishopsgate, 14 February 2017

The first evacuation trial took place on 14 February 2017. At the time of the trial, the construction site consisted of 19 completed core levels and 12 floors in the process of construction. At the time of the trial, there were 184 workers on site who exited the building, 20 workers in the slipform and 164 workers in the rest of the building. During the evacuation, the first worker exited the building after 41 s and the last worker exited after 12 min 46 sec.

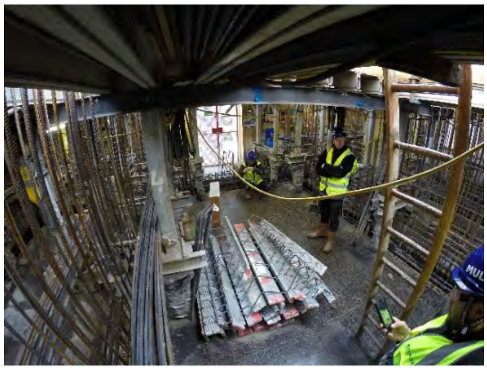
The construction site (see Figure 19) consisted of the following levels:

- Ground (Level 0) to Level 7 (8 levels): completed floors
- Level 8 to Level 11 (4 levels): partially completed floors, with workers laying decking or rebar
- Level 12 to Level 19 (8 levels): only core no completed floors
- Level 19 (20 levels): top of the central temporary stair (highest stair in the building)
- Level 20 (21 levels): 3 decks of the slipform, with the top deck at Level 21 (22 levels) (see Figure 20).

Note: there are 22 levels in Trial 1, including the ground level (Level 0) with the base of the slipform at Level 20 (21 levels) and the top deck of the slipform at Level 21 (22 levels).

Figure 19. 100 BG on the day of the evacuation trial (14/02/17).

(a) View of top deck of slipform.

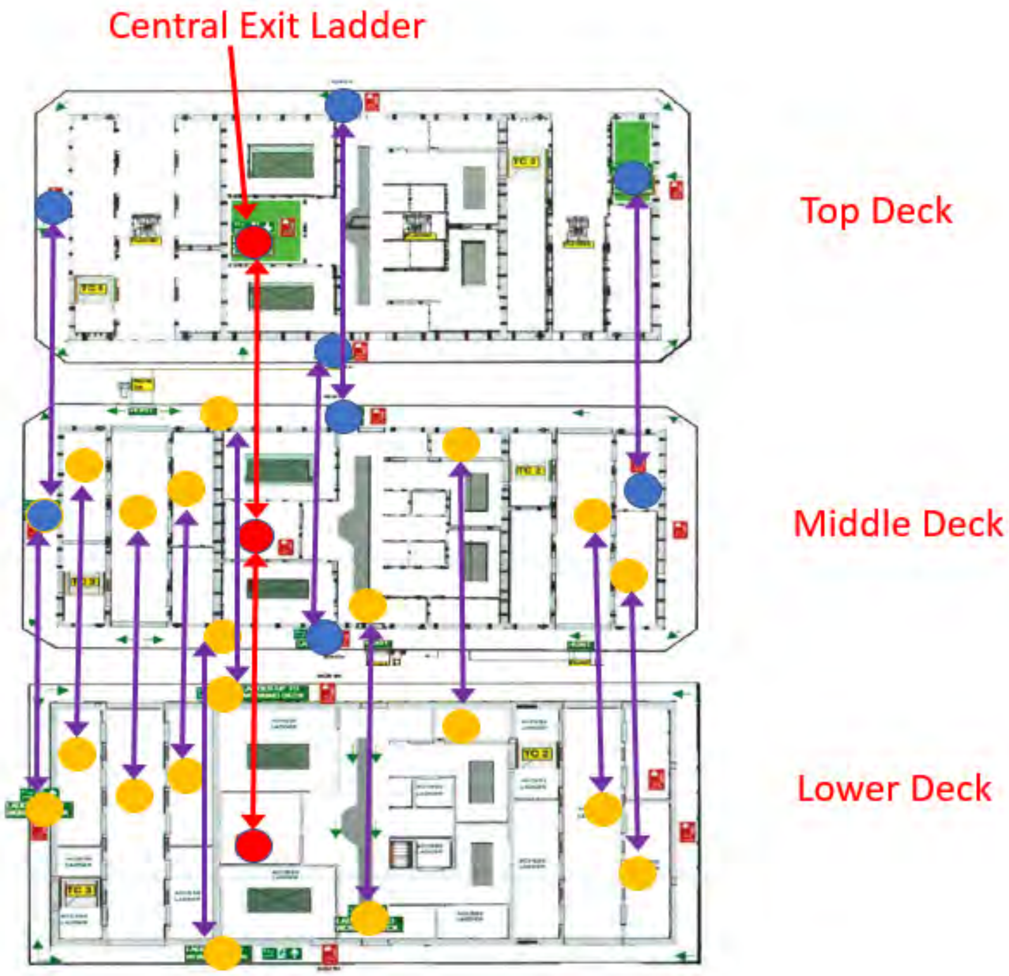


(b) View of middle deck of slipform showing ladder connection between decks.

Figure 20. View of the 100 BG slipform (14/02/17).

The slipform has three decks and is located at Level 20. The lower deck was connected to the middle deck by 10 ladders while the middle deck was connected to the upper deck by four ladders. The slipform had a single exit point which was a ladder that extended from the upper deck to the middle deck and from the middle deck to the level immediately below the lower deck. Access to the exit ladder was only via the upper deck access point, which meant that workers located on the middle or lower deck had to climb the ladders to the top deck before exiting (see Figure 21). Once on the level below the lower deck the worker would transfer to the central temporary scaffold dogleg stair (see

Figure 22). From this point the worker could then continue to descend all the way down to the ground level.



(The red circles and red arrow indicate the location of the main exit route from the slipform.)
Figure 21. Vertical access routes in the slipform at 100 BG.

The state of each floor in the construction site is depicted in Figure 23. This indicates which levels are complete or partially completed (both for floors and core) and whether the floor surface is concrete, decking or rebar.

For the rest of the construction site there were three temporary scaffold dogleg stairs and one hoist (the second 'North' hoist was out of action due to a technical fault, which the workers on site would have been aware of) (as shown Figure 24). The east and west temporary scaffold doglegged stairs went up to the lobby slabs which were under construction. The central temporary scaffold dogleg stair went up to the level below the slipform and could not be accessed by the lobby slabs that were currently under construction. All three temporary scaffold stairs descended to the ground level (see Figure 24).

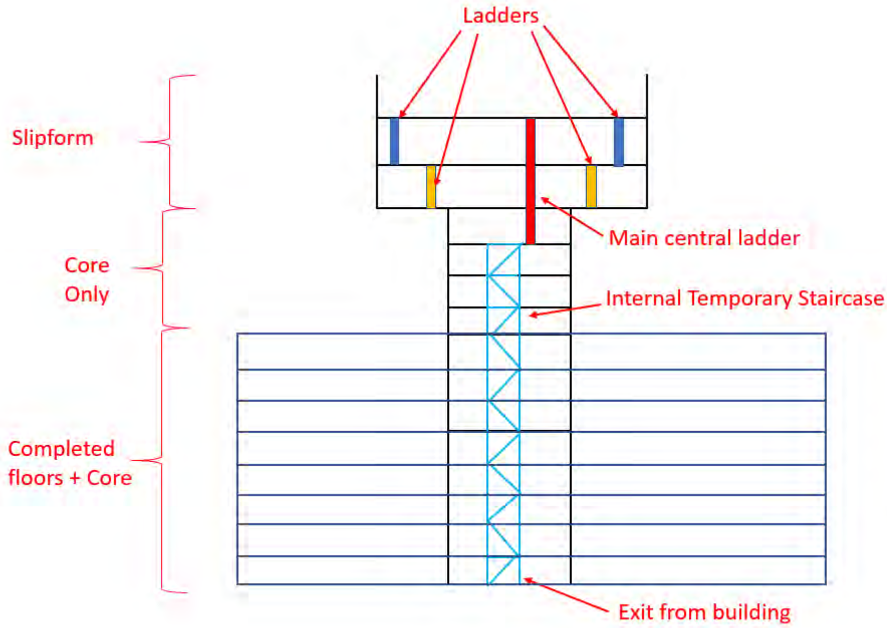


Figure 22. Profile of 100 BG, showing exit routes from the slipform to the ground level (not to scale).

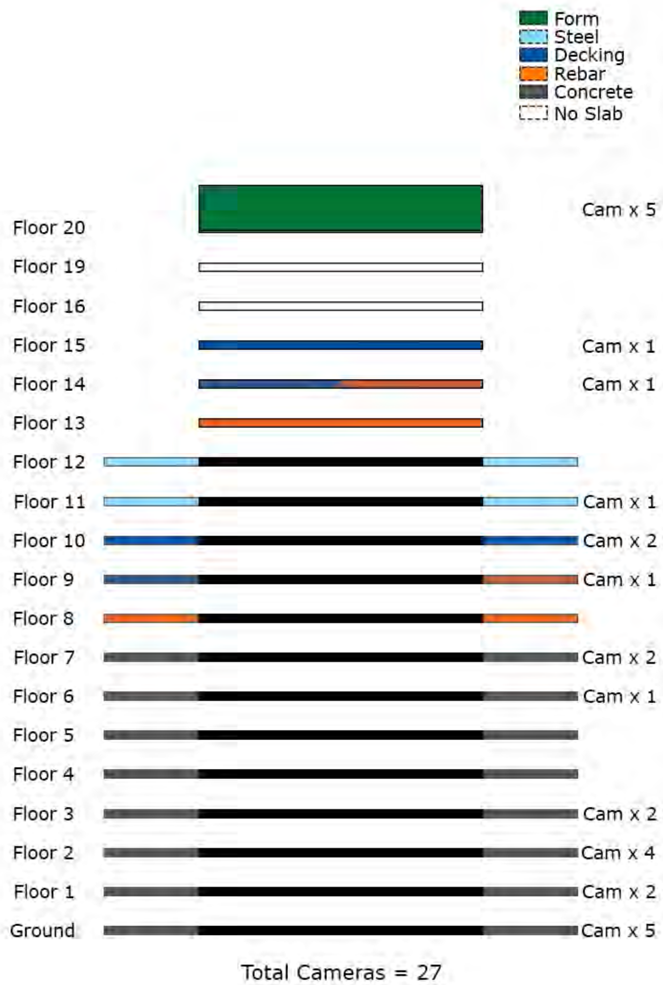


Figure 23. The status of 100 BG during Trial 1 (14 February 2017).

The exits from the three dogleg staircases on the ground level were treated as the end point of the evacuation for the purposes of the project. This is due to workers in the basement level ascending other staircases that also exit at ground floor and who would interact with workers coming from levels above the ground floor.

The slipform was in the process of being reduced in size to accommodate the changing shape of the building after the 19th floor. Therefore, rather than the slipform workers erecting rebar and pouring concrete, they were removing parts of the slipform infrastructure, including outer walls.

Elsewhere on the construction site, workers were laying rebar above metal decking, installing MEP in the core on lower levels and installing glazing/fascia boards to the outer edge of the building.

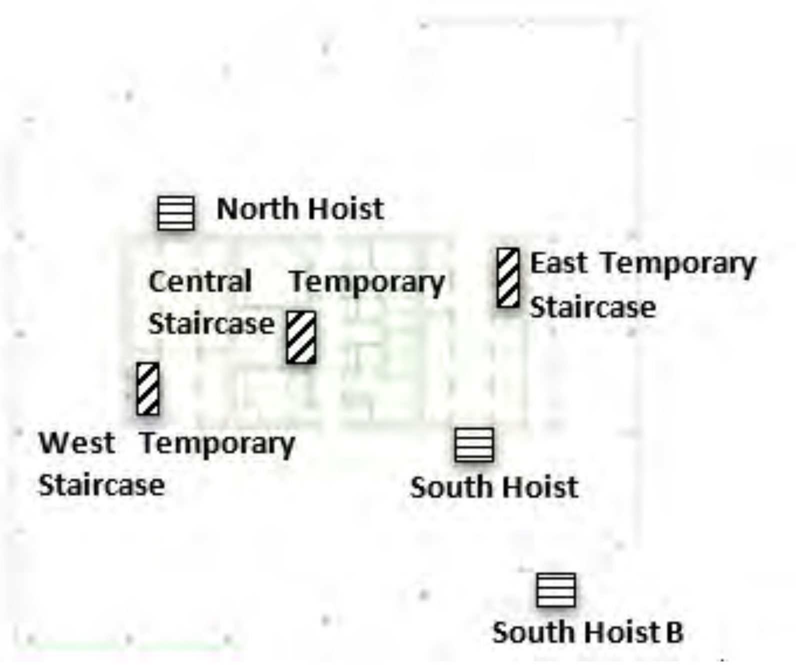


Figure 24. General floor layout for 100 BG during Trial 1, showing locations of vertical access.

Video cameras were set up night before the trial, after most of the workers had left the site (with the exception of the steel erectors who work throughout the night).

The research team involved in undertaking this trial consisted of nine people: six from FSEG and three members of Multiplex (see Figure 25). A member of London Fire Brigade was also present during the trial and helped provide a sense of a real emergency.

From University of Greenwich

- Professor Ed Galea
- Dr Steven Deere
- Dr Hui Xie
- Mr Lazaros Filippidis
- Mr David Cooney
- Dr Lynn Hulse (assisted on the day of the trial)

From Multiplex

- Mr Jim Senior
- Mr Benn Holt
- Mr Ali Ghate

From London Fire Brigade

- Mr Gareth Steele

Figure 25. Part of the trial team for the 100 BG trial on 14/02/17.
From left to right: Prof Ed Galea, (seated front row from left to right) Mr David Cooney, Dr Steven Deere, Dr Hui Xie, Mr Benn Holt, (seated back row from left to right) Mr Jim Senior and Mr Lazaros Filippidis.

The trial team arrived at the site at 18:00 on 13 February (the night before the trial). The team split into two groups with one group installing cameras from the slipform and working their way down the building and the other team starting from the ground floor and working up the building. Each team included a member of the Multiplex staff for health and safety and logistical reasons.

In total there were 27 video cameras installed. The cameras were set up in planned locations to ensure the capture of specific data including response times of workers involved in various tasks, the time to clear the slipform, performance of workers on ladders, performance of workers on the temporary scaffold stairs and the time to exit the building. Presented in Figure 26 is a typical plan showing the planned location of two cameras on Level 10. Camera 16 covers the workers laying the metal decking while camera 19 covers the ladder in the central staircase, the main exit route for the workers from the slipform. The levels at which the cameras were set are presented in Table 5 while Figure 27 depicts setting up some of the cameras. Once set up, each camera was independently checked, and synchronised twice. All the cameras were set up and all work was completed by approximately 01:00 on 14 February.

Table 5. Start/stop times for each camera and which level they were placed on for Trial 1.

Level No.	FSEG CAM No.	Started (hh:mm)	Stopped/Taken Down (hh:mm)
slipform	22	7:09	11:45
slipform	23	7:12	12:12
slipform	29	7:14	12:04
slipform	27	7:17	12:20
slipform	28	7:19	12:24
15	15	7:24	12:30
14	14	7:25	12:34
11	20	7:29	11:29
10	19	7:32	11:22
10	16	7:34	11:17
9	21	7:37	11:12
7	17	7:42	11:02
7	24	7:51	11:00
6	7	7:58	10:53
3	10	8:02	10:45
2	11	8:07	10:13
2	9	8:10	10:26
2	8	8:12	10:29
1	4	8:15	10:06
1	5	8:18	10:10
Ground	1	8:22	10:01
Ground	13	8:24	9:55
Ground	2	8:26	9:52
Ground	18	8:28	9:51
Ground	25	8:30	9:47
2	3	8:42	10:23
3	6	8:45	10:40

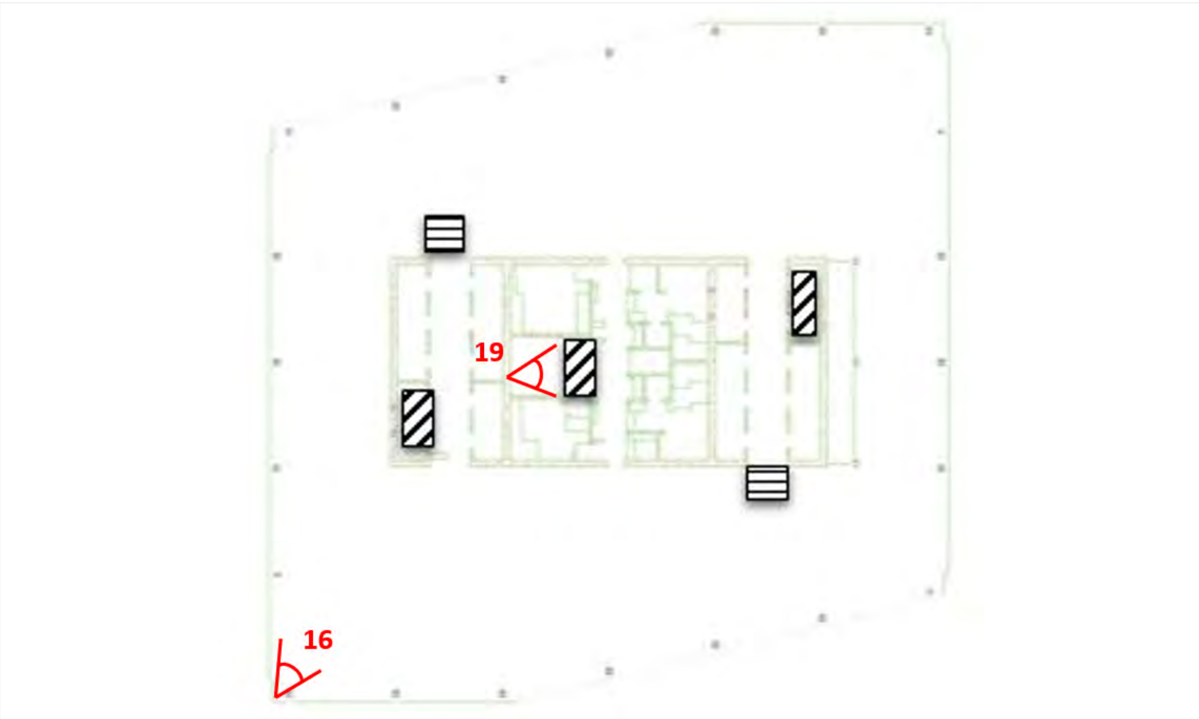
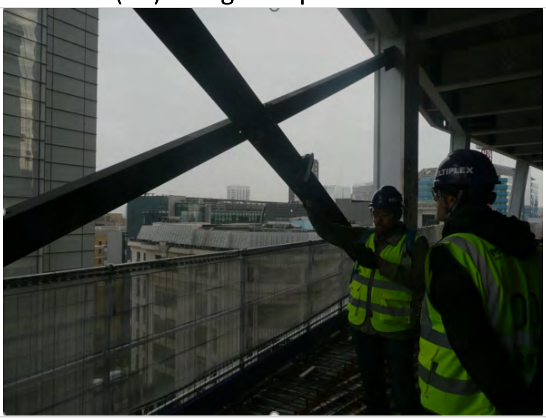


Figure 26. Pre-planned camera locations for Trial 1 100 BG on Level 10.

	
Camera (23) being setup in slipform.	View from camera (23) in slipform.
	
Camera (11) being set up on Level 4 in core.	View from camera (11) on Level 4 in core.
	
Camera (7) being set up on Level 7 on floor.	View from camera (7) on Level 7 on floor.

Camera (4) being set up on Level 3 towards glazing.

View from camera (4) on Level 3 towards glazing.

Camera (18) being set up on ground level with a view of the exit.

View from camera (18) on ground covering exit.

Figure 27. Video camera setup for Trial 1 (100 BG on 14/02/17).

The following morning (14 February 2017) the trial team returned at 07:00 to check all cameras were still in position, activated the cameras and started recording (as shown in Table 5 and Figure 27). The plan was for the fire alarms to be sounded at 09:00 and for the London Fire Brigade to provide a vehicle with sirens which would turn up 3 minutes after the alarm sounded.

The alarms were actually sounded at 08:57, three minutes earlier than planned, which resulted in the fire brigade arriving after the majority of the workers had already evacuated. As a result, the arrival of the fire brigade had little impact on the overall evacuation.

3.3.2 Trial 2, 22 Bishopsgate, 28 February 2017

The second evacuation trial took place on 28 February 2017. At the time of the trial, the construction site consisted of 19 completed levels in the South Core and 13 completed levels in the North Core. At the time of the trial there were no outer floors in the process of being constructed (see Figure 28).

Figure 28. A view of both the North Core and South Core of 22 BG on the day of the trial.

At the time of the trial, there were 231 workers on site, but only 46 workers were actually in the building and hence evacuated from the building. Of these, 43 were located in the North Core and three workers were located in the South Core. Of those workers located in the North Core who exited the building, 30 were in the jumpform and 13 were in the core. Of those workers located in the South Core, one was located in the external staircase and two were on Level 1 in the vicinity of the staircase. During the evacuation, the first worker exited the building after 28 s and the last worker exited the building 9 min 14 sec after the start of the alarm.

The construction site consisted of the following levels:

- North Core: Ground to Level 13: only core, with no completed floors
- North Core: three decks of the jumpform
- South Core: Ground to Level 19: only core with no completed floors
- South Core: three decks of the jumpform.

The state of each floor in the construction site is depicted in Figure 29. This indicates which levels are complete or partially completed (both for floors and core) and whether the floor surface is concrete, decking or rebar.

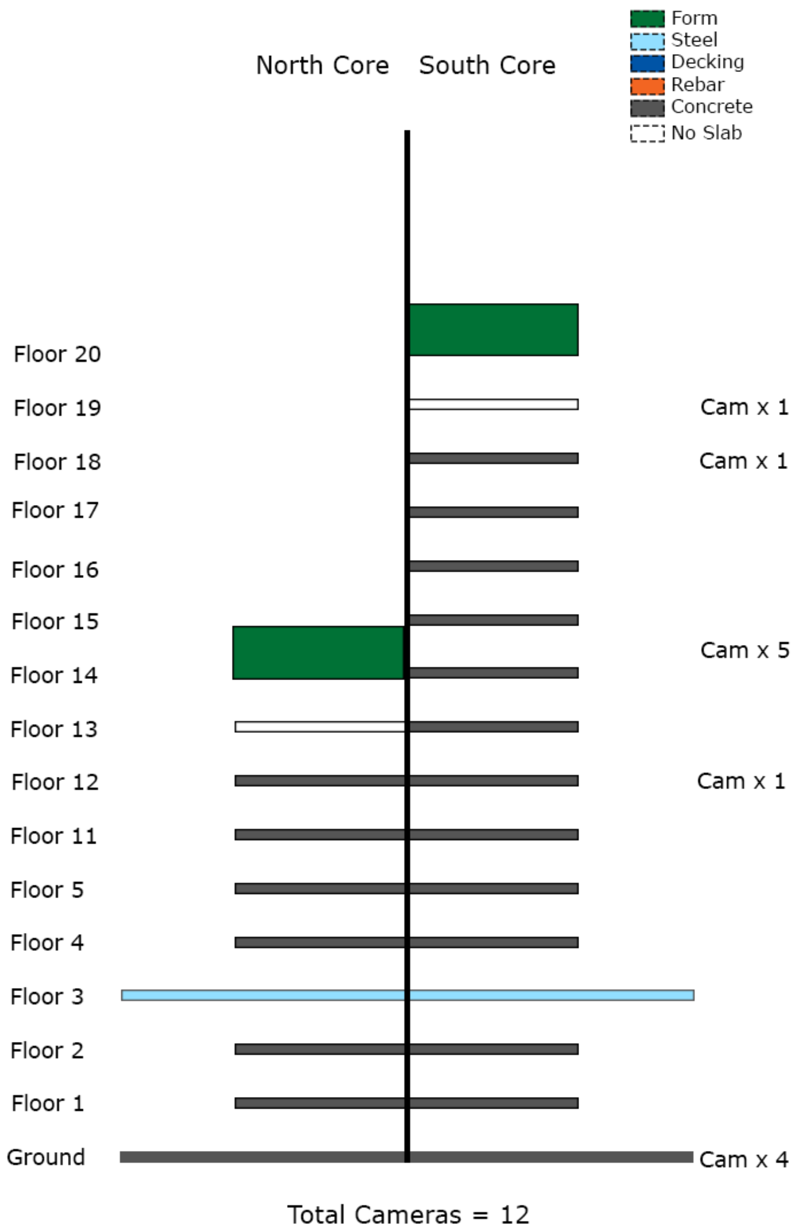


Figure 29. Status of construction at 22 BG during Trial 2 (28 February 2017).

The jumpform has three decks: in the North Core at Level 14 and in the South Core at Level 20. As only the North Core jumpform was occupied, the remainder of the description will only cover the North Core. There was only one exit from the jumpform, which was via a hanging stair arranged in the form of a doglegged stair which was only wide enough to accommodate a single person across a stair tread. The hanging stair could only be accessed via the top deck of the jumpform. There were seven ladders located in the jumpform, five connecting the lower deck to the middle deck and two connecting the lower deck to the upper deck. To exit the jumpform, workers located on the middle deck would have to climb down to the lower deck and then transfer to the ladders that would take them to the upper deck (see Figure 30). The jumpform hanging stair extended four levels below the bottom of the jumpform, down to the 10th level, at which point the worker would have to walk across the completed lobby floor to the external temporary scaffold doglegged stair (see Figure 31). From this point the worker could then continue to descend all the way down to the ground level.

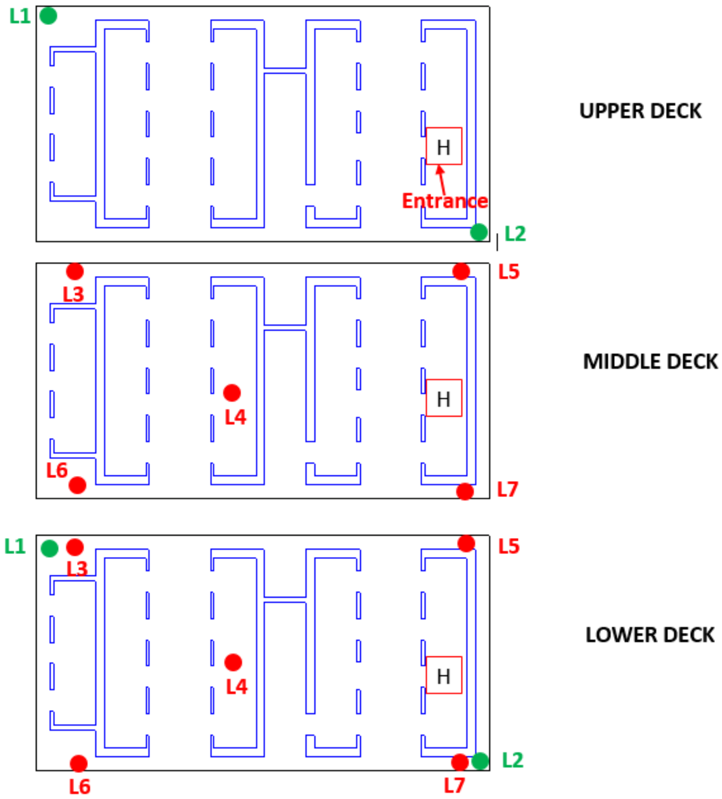


Figure 30. Vertical connectivity within the jumpform at 22 BG, showing the location of seven ladders (L1–L7) and the hanging staircase (H). The entrance to the hanging staircase is marked on the upper deck.

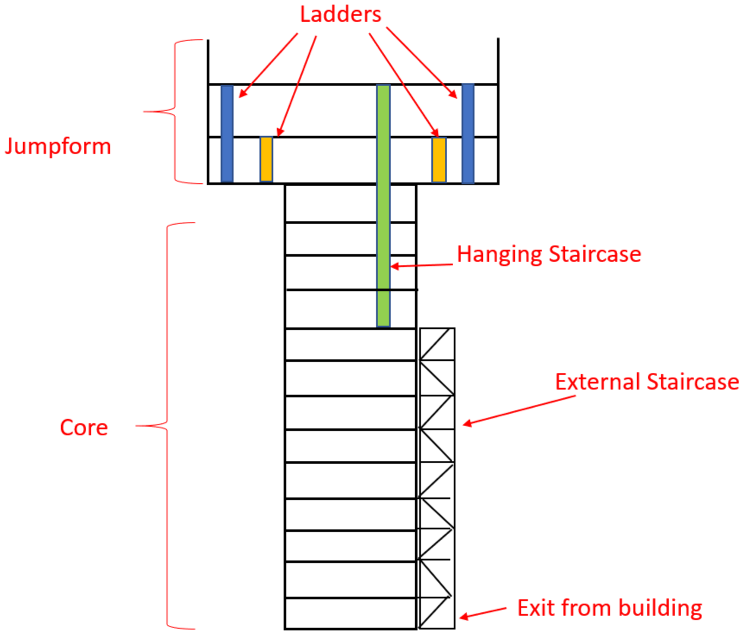


Figure 31. Illustrated profile of the North Core of 22 BG, showing vertical connectivity (not to scale).

The bases of the external stairs (one for the North Core and the other for the South Core) ended on the ground level as indicated in Figure 32. Within each core was also a hoist; however, as these were not part of the site's evacuation plan and were not to be used in the event of an emergency, they were not considered in this trial and so the bases of the hoists were not monitored. Thus the exit points of the temporary scaffold stairs on the ground level were treated as the end point of the evacuation for the purposes of the project.

As only the core of the building existed on the day of the trial, the only works going on were in the two jumpforms. This consisted of installation of rebar in preparation of a concrete pour.

Figure 32. Exit to North and South Cores via external temporary scaffold dogleg stairs on the ground level of 22 BG.

Video cameras were set up the night before the trial, after the workers had left the site. The research team involved in undertaking this trial consisted of nine people: six from FSEG and three members of Multiplex.

From University of Greenwich
- Professor Ed Galea
- Dr Steven Deere
- Dr Hui Xie
- Mr Lazaros Filippidis
- Mr David Cooney
- Dr Lynn Hulse (assisted on the day of the trial)

From Multiplex
- Mr Jim Senior
- Mr Carl Beisser
- Mr Neal Cook

The trial team arrived at the site at 18:00 on 27 February (the night before the trial). The team split into two groups with one group installing cameras in the North Core and the other team installing cameras in the South Core. Each team included a member of the Multiplex staff for health and safety and logistical reasons.

In total there were 12 video cameras installed. The cameras were set up in planned locations to ensure the capture of specific data including response times of workers involved in various tasks, the time to clear the jumpform, performance of workers on ladders, performance of workers on the temporary scaffold stairs and the time to exit the building. Presented in Figure 33 is a typical plan showing the planned location of two cameras in the upper jumpform. Cameras 16 and 18 cover the workers in the jumpform installing rebar in preparation for a concrete pour.

The levels at which the cameras were set are presented in Table 6 while Figure 34 depicts setting up some of the cameras. All the cameras were set up and all work was completed by approximately 20:40 on 27 February.

Table 6. Setup/take down times for each camera and which level they were placed on for Trial 2.

Level No.	FSEG CAM No.	Setup (hh:mm)*	Started (hh:mm)	Stopped/Taken Down (hh:mm)
Ground	2	17:20	7:36	10:46
Ground	3	17:29	7:34	10:40
Ground	1	17:55	7:02	10:56
Jumpform	4	18:43	7:13	9:51
Jumpform	16	18:57	7:14	9:47
Jumpform	18	19:10	7:15	9:55
Jumpform	11	19:24	7:17	10:00
Jumpform	12	19:45	7:21	10:03
13	13	19:48	7:10	10:13
12	14	20:08	7:09	11:28
10	15	20:40	7:45	11:14
Ground	7	08:38	8:40	11:44

* Night before trial.

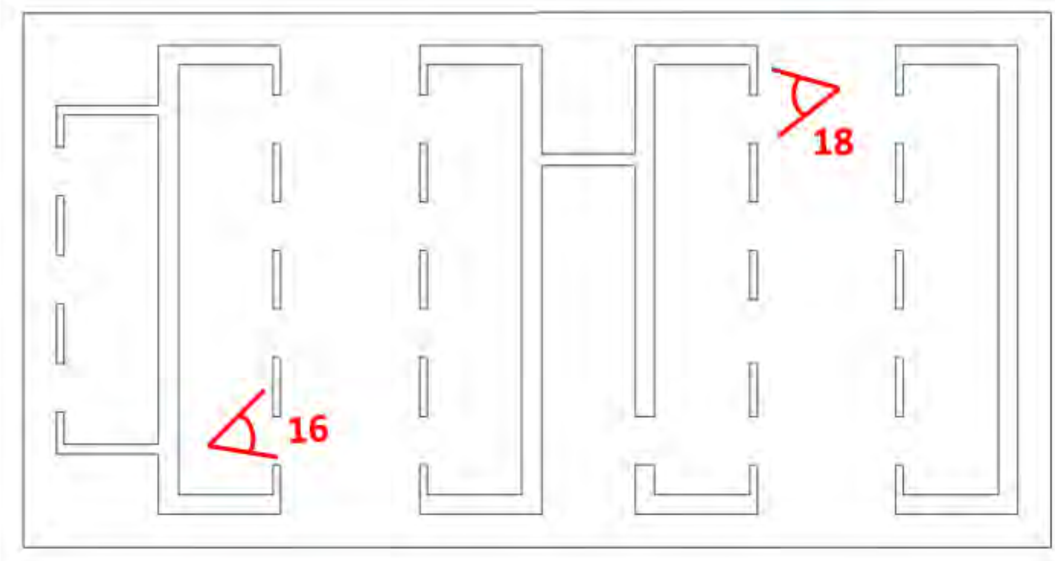
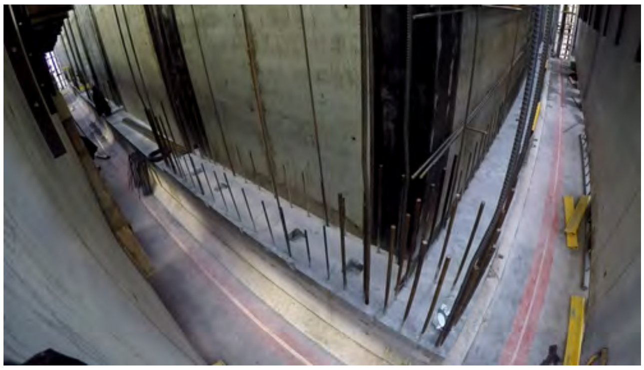


Figure 33. Pre-planned camera locations for Trial 2 22 BG on the upper jumpform level.

Camera (5) being set up in jumpform.



View from camera (5) in jumpform.

Camera (9) being set up on Level 10 on floor, looking at the top of the external staircase.

View from camera (9) on Level 10 on floor.

View from camera (2) on ground covering exit.

Figure 34. Video camera setup in second trial (22 BG on 28/02/17).

The following morning (28 February 2017) the trial team returned at 07:00 to check all cameras were still in position, activated the cameras and started recording (as shown in Table 6). The trial commenced on time with the alarm sounding at 09:00.

In total 46 workers were observed exiting the building: 43 of these exited the North Core via the externally located temporary scaffold doglegged stairs and three workers exited the South Core via externally located temporary scaffold doglegged stairs. Of the three workers exiting the South Core, one was already descending the external staircase when the alarm sounded and the other two were on Level 1 and near to the staircase.

While a total of 231 workers were recorded leaving the construction site, it is unclear why so few were in the building at the time of the alarm.

3.3.3 Trial 3, 100 Bishopsgate, 4 October 2017

The third evacuation trial took place on 4 October 2017. At the time of the trial, the construction site consisted of 38 completed core levels and 33 floors in the process of construction. On the day of the trial the core had reached its final height and so the slipform had been removed.

The exit routes from the building consisted of three temporary scaffold staircases all located within the core, two of dogleg configuration and one of parallel configuration. The temporary stairs extended down to Level 6 at which point the workers would have to exit the temporary stairs and transfer to the permanent stairs which continued to the ground level. All three temporary scaffold staircases could be accessed from all levels in the building.

Two hoists and a common goods tower (consisting of three hoists used to transport workers and equipment/materials to different levels) were present. The hoists were used during the evacuation as set out in the construction site's emergency plan.

The three permanent stairs ended (started) on the ground level where the workers could exit the building. In addition, workers could also exit the building from the first level where there was an exit to the welfare area (canteen and changing/locker rooms). For the purposes of this trial, there are four final exit points: the exit points from the three permanent stairs on the ground level and the exit point onto the first floor from the welfare area. The site exit on the ground level was not used as the exit point due to workers located in the basement coming up and exiting the site.

The majority of works occurring on the day of the trial involved installing exterior glazing and facia, installing mechanical electrical and plumbing (MEP) components such as air conditioning, general pipework and electricity supplies, and installing metal decking on the upper floors. The majority of this work was taking place on the floors halfway up the building, where the team deployed a large number of video cameras.

Video cameras were set up the night before, after the workers had left (with the exception of steel erectors who worked throughout the night). The trials team arrived on site at 18:00 on 3 October, the night before the trial. The team split into two groups with one group installing cameras from the top level and working their way down and the other team starting from the ground level and working up. For health and safety and logistical reasons, both teams were accompanied by a member of Multiplex. All the cameras were set up and all work was completed by 23:30 as shown in Table 7.

Table 7. Setup/take down times for each camera and which level they were placed on for Trial 3.

Level No.	FSEG CAM No.	Setup (hh:mm)*	Started (hh:mm)	Stopped/Taken Down (hh:mm)
38	16	19:10	7:58	10:00
38	13	19:15	7:59	09:58
37	29	18:50	8:02	10:04
37	23	18:50	8:01	10:03
33	8	20:05	8:06	10:11
33	27	20:07	8:08	10:09
33	26	20:10	8:11	10:10
27	4	20:30	8:15	10:20
27	5	20:30	8:14	10:18
23	2	21:00	8:18	10:24
22	18	21:30	8:19	10:29
21	11	21:26	8:20	10:31
20	6	21:15	8:21	10:33
19	24	21:32	8:22	10:36
6	7	22:15	8:31	10:50
6	25	22:15	8:36	10:52
6	15	22:20	8:33	10:56
6	9	22:30	8:35	10:57
10	21	22:40	8:27	10:45
1	28	22:54	8:39	11:04
1	22	23:04	8:40	11:02
Ground	20	23:13	8:42	11:08
Ground	12	23:15	8:43	11:07
Ground	19	23:22	8:44	11:13
Ground	CCTV	-	-	-
Ground	10	08:48	8:48	11:11

* Night before trial.

The trial team returned the following morning (4 October) at 07:00 to check all cameras were still in position, powered up all the cameras and started the recording. The fire alarm was planned to sound at 09:00. The alarm sounded at 09:00 and a total of 308 workers evacuated the building in 18 min 18 sec.

The state of each level in the construction site is depicted in Figure 35. This indicates which levels are complete or partially completed (both for floors and core) and whether the floor surface is concrete, decking or rebar.

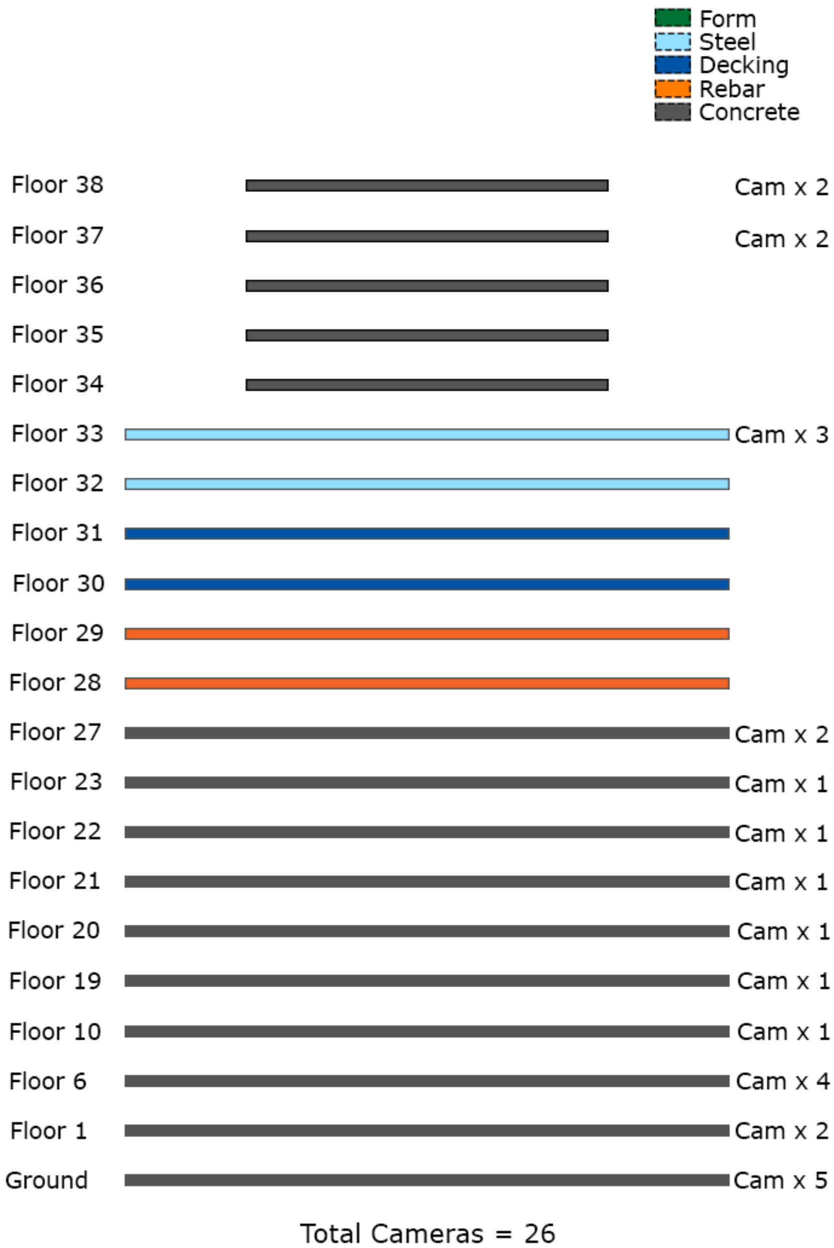


Figure 35. The status of 100 BG during Trial 3 (4 October 2017).

The team required to carry out the trial consisted of four FSEG staff and one member of Multiplex.

From University of Greenwich

- Dr Steven Deere
- Dr Hui Xie
- Mr David Cooney
- Mr Michael Joyce

From Multiplex

- Mr Ali Ghate

3.3.4 Trial 4, 22 Bishopsgate, 16 November 2017

The fourth and final evacuation trial took place on 16 November 2017. At the time of the trial, the building consisted of 38 completed levels in the South Core and 32 completed levels in the North Core along with 20 levels in the process of construction (see Figure 36). The building had two jumpforms, one for each core, and both jumpforms had three decks. The jumpform in the North Core was located at Level 33 while in the South Core it was located at Level 39. The exit route from the building consisted of a single temporary scaffold dogleg staircase which ran from Level 28 down to Level 8 where workers would transfer to a permanent staircase which would take them to the ground floor. There were a total of four hoists in the building: two hoists providing vertical access for each core.

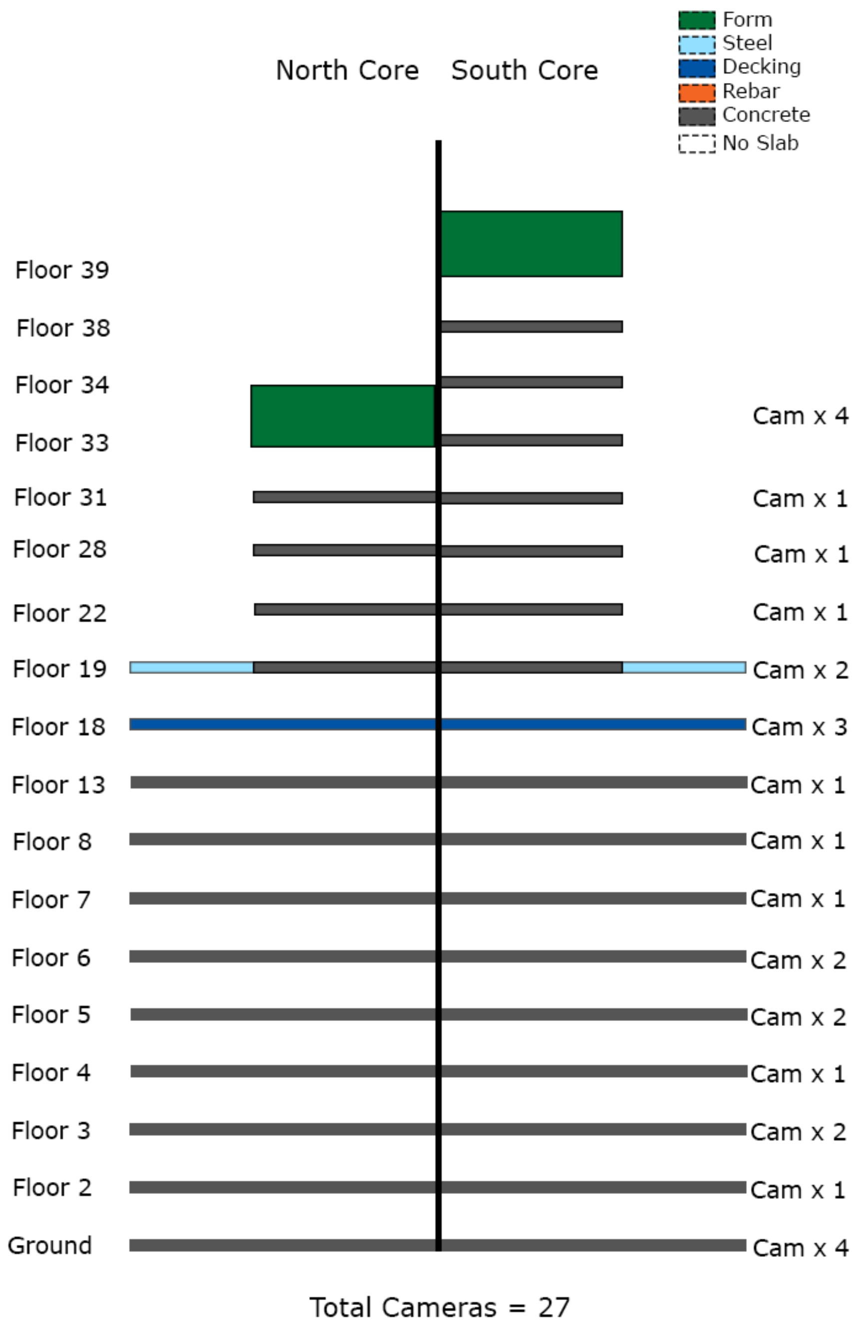


Figure 36. State of progress at 22 BG during Trial 4 (16 November 2017).

Video cameras were set up the night before, after the workers had left (with the exception of steel erectors who work throughout the night). The trial team arrived at the site at 18:00 on 15 November (the night before the trial). The team started setting up the video cameras from the jumpform and worked down. On each level, the team would split up setting up cameras. Once a level was completed, the team would move down to the next level and repeat the process. For health and safety and logistical reasons, the team was accompanied by two members of Multiplex. All cameras were set up and all work completed by approximately 23:00 (see Table 8) with the trial team leaving the site at about midnight.

The trial team returned the following morning (16 November) at 07:00 to check all cameras were still in position, powered up the cameras and starting recording. The fire alarm was originally planned to sound at 09:00. The alarm was sounded at 09:33 and 394 workers evacuated from the building in 25 min 18 sec as shown in Table 8.

Table 8. Setup/take down times for each camera and which level they were placed on for Trial 4.

Level No.	FSEG CAM No.	Setup (hh:mm)*	Started (hh:mm)	Stopped/Taken Down (hh:mm)
33 (Jumpform)	22	18:45	08:29	10:30
33 (Jumpform)	7	18:50	08:29	10:30
33 (Jumpform)	5	19:05	08:30	10:34
33 (Jumpform)	8	19:05	08:27	10:34
31	21	19:20	08:34	10:42
28	29	19:28	08:37	10:46
22	15	19:52	08:44	10:52
19	4	20:17	08:50	10:59
19	26	20:28	08:48	10:57
18	12	20:18	08:52	11:04
18	23	19:43	08:55	11:05
18	16	19:55	08:55	11:11
13	13	20:44	09:00	11:16
8	2	21:00	09:05	11:22
7	28	21:20	09:07	11:28
6	19	21:25	09:10	12:30
6	27	21:27	09:10	12:24
5	20	21:45	09:12	11:38
5	6	21:45	09:14	11:45
4	17	22:05	09:14	11:51
3	10	23:27	09:30	-
3	18	22:11	09:18	09:58
2	24	22:24	09:22	12:06
G	1	22:37	09:23	12:10
G	25	22:47	09:26	10:10
G	14	22:56	09:24	10:13
G	9	23:07	09:30	09:54

* Night before trial.

The team required to carry out the trial consisted of four FSEG staff and two Multiplex staff.

From University of Greenwich

- Dr Steven Deere
- Dr Hui Xie
- Mr David Cooney
- Mr Michael Joyce

From Multiplex

- Mr Carl Beisser
- Mr David Miller (assisted with setup of camera equipment)

3.4 Equipment required

Performance data consisting of response times, travel times on ladders and temporary scaffold stairs were collected using strategically located video cameras. The research team had some 30 video cameras available for data collection. However, it was necessary to purchase additional cameras to provide additional coverage but also to address an important issue that was noted from the pilot study in 2013.

During the pilot study, several of the original video cameras failed to record the trial as the internal hard drives within the cameras shut down sometime prior to the start of the trial. It was determined that the hard drives shut down due to excessive vibration generated by works on the construction site. These cameras had been attached to steel beams which vibrated with high frequency when there were heavy works such as banging or drilling on site. As part of this project a number of additional video cameras (GoPros) and associated clamps were purchased which utilised an SD memory card rather than an internal hard drive. Through testing, these cameras were shown not to be prone to failure due to vibration. In addition the GoPro cameras had the advantage of being smaller than the earlier video cameras which made them easier to deploy and could be operated remotely using a Wi-Fi enabled device, such as a mobile telephone. This was a useful feature when deploying cameras at height or in awkward locations such as in corners where it is not always possible to see the camera's screen, and thus its field of view, or to be able to press the record button.

In total 30 GoPro Hero 4 cameras were used to collect the video data during these trials. Along with the video cameras, special clamps were used which provided the greatest flexibility for deploying the GoPro cameras on a construction site. Extended-life batteries were also used to power the cameras beyond the standard two hours as it was anticipated that the cameras would be deployed more than three hours prior to the start of the trials. The team also had a set of walkie-talkies so that they could communicate while on the construction site (see Figure 37).

In addition to the purchased camera equipment, small black plastic bags were used to cover the cameras, providing basic protection from the elements and camouflage (see Figure 37f). Cable ties and tethers (see Figure 37b) were also used to offer additional security to the battery packs and clamps. A large tape measure was used to take essential dimensions from each construction site, such as stair and landing dimensions. A typical installation of a video camera on site is depicted in Figure 38.

For each trial all the equipment was packed into two equipment cases and transported to the site the night before the trial for installation (see Figure 39). The two cases also made it easier for the two camera installation teams to carry the equipment through the construction site.

(a) Long-life batteries being charged.

(b) Long-life batteries with ties prepared for mounting on clamps.

(c) 30 GoPro cameras connected to long-life batteries.

(d) Video cameras and special clamps used on the project.

(e) Collection of all the equipment to be used on the trials.

(f) Demonstration of mounted camera, complete with weather-protecting black plastic bag.

Figure 37. Equipment used in all four evacuation trials.

Figure 38. Example set up of a GoPro video camera.

Figure 39. Equipment being packed back into the equipment cases at the end of a trial.

3.5 Questionnaires

3.5.1 Introduction

In addition to video data capture to characterise the workers' movement and behaviour during the evacuation trials, a questionnaire was devised which would attempt to obtain information which cannot be derived from the video footage, such as the workers' level of risk perception, their knowledge of evacuation procedures, etc. The questionnaire was divided into five sections:

- **demographics** (age group, level of experience, etc.)
- **initial location** at the time of the alarm
- **response to the alarm** (Did they think it was a real emergency? What was the first thing they did after recognising the alarm?)
- **exit route taken and why that route** (Was it the route they entered on? Did they follow others?)

- **perceived level of risk** (Did they feel in danger during the evacuation trial? Do they normally feel in danger on a construction site i.e. in non-emergency situations?).

3.5.2 General design

The questionnaire was based on an earlier questionnaire used in the 2013 pilot trial. This was refined based on experience from the pilot trial, e.g. attempt to reduce the number and complexity of the questions, need for multiple languages. The questionnaire also needed to be made site specific regarding use of hoists, wayfinding, etc.

The questionnaire went through several internal iterations (distributed to both UoG team members, Multiplex and the advisory board for comments) before it was finalised. Once the final questionnaire design was agreed upon, the participant information and consent page, and the study questions, were translated by a bilingual individual (from the Multiplex management team) into Romanian, as this was one of the most common languages other than English spoken by workers at both the 100 Bishopsgate and 22 Bishopsgate sites. The Romanian version was subsequently translated back into English by a different individual (from the University of Greenwich), to check that no loss of meaning or quality had occurred during the translation process. As well as being available in two different languages, the questionnaire was available for completion in two different forms: a paper questionnaire and an online survey. The structure and content of both were identical. The online survey was hosted on a secure server at the University of Greenwich and managed by a member of the trial team. The survey was tested prior to the trial to ensure that it worked on a variety of internet browsers and on mobile devices.

Data collection during Trial 1 at 100 Bishopsgate took place in the site canteen during workers' breaks. Posters were put up around the canteen advertising the study and these also displayed a QR code for the online survey. Additionally, paper slips were placed on all the canteen tables with the web address for the online survey. Once breaks began and workers started arriving in the canteen, the trial team waited for them to clean themselves first, then approached individuals in person, verbally explained the study to them, answered any questions they had, and requested their participation. Workers were informed that the questionnaire would take up to approximately 20 minutes to complete. A number of workers declined to participate as they wished to use their downtime for other purposes. A further number were not approached due to being engaged in phone calls or eating hot meals. Several more were approached and agreed to take part but ran out of time to complete their questionnaires. Due to these issues, the resultant low number of returned questionnaires (see Section 4.1.2), and the amount of missing data within returned questionnaires, it was decided that further amendments would take place for the next trial.

For Trial 2 at 22 Bishopsgate, a much shorter version of the questionnaire (average time to complete approximately 5 to 10 minutes) was designed; it still covered background information, site location and task, aspects of the evacuation, and risk perception and risk-taking. The questionnaire was also simplified, with branching (i.e. splitting of questions based on previous answers, for example "If you answered X, please now go to question A. If you answered Y, please skip forward to section B") being removed wherever possible. The questionnaire was again available in English and Romanian, and in paper and online forms. The data collection location was changed – this time, workers were approached in person by the trial team once outside at the evacuation assembly point.

Apart from a few workers who again took the opportunity to make phone calls, most were unengaged in any other activity while at the assembly point and therefore were noticeably more receptive to participating in the study. Despite this increased co-operation, the window for data collection was much shorter, i.e. there was only approximately 10 minutes between the first worker arriving at the assembly point and the announcement that the evacuation had ended and all workers should return to their jobs. This meant that a number of workers (particularly those who had been operating higher up the building and therefore were the last to arrive at the assembly point) ran out of time to complete or even start the questionnaire. As a result, the number of returned questionnaires was again lower than the total amount hoped for (see Section 4.2.2). Subsequent attempts to gather sufficient questionnaire data also met challenges and, unfortunately, no correctly completed questionnaires were collected in the last two trials.

Following collection of the completed questionnaires, all questionnaire data was manually entered into and analysed using the software package IBM SPSS Statistics 22. In inferential statistical tests, p-values of less than 0.05 meant a statistically significant difference or association was detected.

The complete questionnaires (English version) can be found in Appendix 2. In the next section the main questions are discussed, providing an explanation for the rationale for each.

3.5.3 The questions

A search for literature related to construction site evacuations and worker risk perception and risk-taking was conducted in order to help inform the questionnaire design; however, this uncovered little useful information. Thus, more general research literature on evacuations, risk perception and risk-taking in the domain of health and safety was consulted.

The Trial 1 questionnaire included the following topics:

1. **Background –** The questionnaire first enquired into the workers' background, i.e. socio-demographic characteristics such as their age and their first language, and how long they had been working at their site. Age was of interest because it is known to affect walking speeds during evacuations [61, 85] and therefore a site with an older workforce might display more reliance on devices such as hoists to help them evacuate quickly. Language was important because the UK (or more specifically the London) construction site workforce is diverse in terms of nationalities, yet on-site safety communications may come via English-speaking management or via other means where the meaning of the messages may not be as universal as first thought [86–88]. Thus, a site with a larger proportion of workers for whom English is not their first language might display a lesser awareness of safety and evacuation procedures. The length of time that workers had been at their site was of interest since the evacuation literature shows that familiarity plays a role in the choice of evacuation route, i.e. people with less experience of working in their location tend to exit via the same route by which they entered, even if a quicker route is available, due to uncertainty about any other route [89]. Thus, a site with a less experienced and therefore less familiar workforce might display such a tendency.
2. **Location on site** – It was important to know which part of the building workers were in at the start of the evacuation trial so that self-reported responses could be compared with responses observed in the video footage.
3. **Believability of alarm** – Evacuation responses (e.g. how quickly people react to an alarm and start evacuating) can vary in part according to whether the alarm is thought to represent a genuine emergency or not [90]; a site where workers are more sceptical about the meaning behind an alarm sounding might display a longer overall response time, as observed on the video footage.
4. **Evacuation procedures** – Construction sites provide evacuation plans as part of their site safety procedures. The question is: will workers be aware of the correct procedure and will they remember it and follow it during an evacuation? As already mentioned above, there are certain factors that may reduce awareness or comprehension of communications about safety procedures, factors that may reduce the likelihood of evacuation being initiated immediately upon hearing an alarm, and factors that may influence people's choices about how to exit to a place of

safety, even when more appropriate choices are available. So it cannot automatically be assumed that just because an evacuation plan exists, workers on a site will (a) know what the stated correct procedure is, and (b) follow it by immediately leaving and exiting via the evacuation route recommended in the plan.

5. **Task importance** – If construction site workers perceive pressure from management to complete tasks then this work pressure can lead indirectly to a negative safety climate, which in turn can lead to unsafe behaviours [91]. A site where workers perceived greater work pressure might be a place where workers would delay evacuating in order to try to complete their tasks. It was therefore of interest to compare how important the workers in this study felt it was to complete their task before evacuating compared to their perceptions of the level of importance their employer would place on them first completing their task.
6. **Evacuation trigger** – While alarms are designed to trigger evacuation, other cues can sometimes be just as or more effective in this regard, e.g. a verbal instruction to evacuate from an authority figure, observing the crowd react to a situation [89]. Therefore, the questionnaire inquired as to what cue was the one that prompted workers to start evacuating.
7. **Risk-taking, risk perception** – Individuals differ in terms of how they perceive the risk present in certain contexts and in terms of how willing they are to take risks in certain contexts; individual differences in risk perception have been linked to the decision to take protective action in an emergency [92], while individual differences in risk-taking have been linked with safety climate and behaviours on constructions sites [91]. However, context is important [93]. Thus, the questionnaire in this study asked workers to rate (i) the level of risk they perceived during the evacuation, (ii) the level of risk they perceived when working under everyday conditions on their current site, and (iii) the level of risk they perceived when working under everyday conditions on construction sites in general. These were measured using a four-point scale consisting of "not at all", "a little danger", "some danger" and "extreme danger" in response to a question of the type "Did you sense you were in danger during the evacuation?"

   Moreover, to create a new risk-taking measure for the workers in this study, the trial team drew upon two existing measures that actually considered context during their design. The first was the domain-specific risk-taking scale by Blais and Weber [93] and the second was the road-user risk-taking scale by Hulse, Xie and Galea [94]. Of the nine items that comprised the workers' risk-taking measure, four were unique from the Hulse et al. scale, three were unique from the Blais and Weber scale, and two were common to both scales. The replies to the various items were measured using a seven-point Likert Scale. All items described risky behaviours, ones that were deemed to have some relevance to working on a construction site or depicted scenarios that might arise (at least in workers' minds) if they were to 'down tools' and evacuate from a site. That is, the items encompassed behaviours relating to one's safety around vehicles, a reluctance to use protective equipment, engaging in activities at great heights, disobeying authority or rules, and a willingness (or reluctance) to lose a day's wages. As people may sometimes be cautious about admitting to risky behaviours, the risk-taking measure was compared with a tool used by Multiplex during their worker induction programme – this tool asks about risk-taking to highlight to workers that irrespective of their personal appetite for taking risks outside of work, once they are on site they must put safety first. It was noticed that some of the items on this tool were similar to those in the workers' risk-taking measure and this reassured the trial team that there would be few, if any, objections to answering the items.

3.6 Walking speed trials

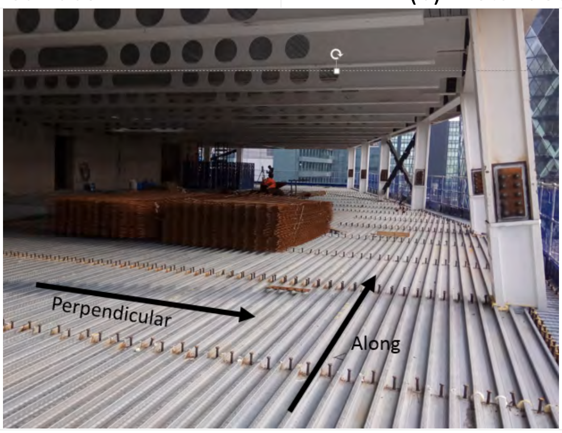
3.6.1 Introduction

During the visits to the construction sites it was noted that there were three different types of surfaces that workers could be required to walk over during an evacuation. These surfaces consisted of concrete (see Figure 40a), metal decking with rebar (see Figure 40b) and metal decking (see Figure 40c). Furthermore, it soon became apparent that unlike the other surfaces, when walking over the metal decking, the direction of travel had an impact on walking speed: in particular it was noted that walking along the direction of the ridges of the decking was more difficult (i.e. slower) than walking perpendicular to the ridges (see Figure 40c).

At the time of the alarm, construction site workers could be located anywhere on a particular floor and so it would be extremely difficult (if not impossible) to accurately monitor the physical movement of sufficient workers over sufficient distance on all three surfaces (four sets of conditions) to make accurate estimations of walking speeds. It was concluded that the only way to collect the required data was to undertake additional laboratory style experiments involving workers walking across the various floor surfaces. As these additional experiments were to be conducted it was also decided to collect travel speed data for workers travelling on the temporary scaffold stairs, of which there were two types: dogleg stairs and parallel stairs (see Figure 17).

(a) Concrete surface.

(b) Metal decking with rebar.



(c) Metal decking.

Figure 40. Three walking surfaces commonly found on construction sites.

In both cases, the stairs are only one lane wide and, as a result, only one person can be accommodated on the same step at a time, making overtaking or contraflow difficult or impossible. A key difference between the two types of temporary stairs is the size and location of the landings between flights of stairs. Dogleg stairs have a small landing which is as wide as the width of two stairs and typically only requires the person to take one step from one flight of stairs to the next. The dogleg stairs tend to be steeper than normal building stairs which may impact the speed at which people travel on the stairs, compared to normal stairs. For parallel stairs the landing tends to be slightly longer than the horizontal length of a flight of stairs and requires the person using the stair to walk a short distance to reach the next flight of stairs. Furthermore, the flights in parallel stairs are directly above each other, which, depending on the height of the person, can result in restricted headroom, which can in turn impact travel speed on the stairs (see Figure 41).

Figure 41. Limited head clearance on a temporary scaffold parallel stair (depicted person is 1.8 m tall).

3.6.2 General planning for the walking speed experiments.

The walking speed trials were to be conducted at both construction sites at various times during the construction process. The walking speed experiments had to be scheduled so as to have sufficient available workers who were able/prepared to lose about 30 minutes from their working day to participate, ensure that the correct types of surfaces/stairs were available and closely located together, and to cause the minimum disruption to the construction process. As the nature of the construction site environment was constantly changing, this required numerous site visits to ensure that the suitable locations were available during the suggested windows of opportunity.

To determine the impact of surface type on walking speed it was desirable that each participant travelled over each of the four types of surface so a comparison of walking speeds could be made on a person by person basis. To achieve this a general path was defined that would take participants over each of the required surfaces and at least one type of temporary stair in minimum time (see Figure 42).

The experiments would involve each participant walking a distance of 18 to 20 m over each surface twice (going one way and then walking back) providing two data points for each surface type. The challenge was to identify a suitable location for each trial where the required length of surface for each surface type were closely co-located. All data collection was achieved by using suitably positioned synchronised video cameras to record the start and end point of each leg and a brief questionnaire.

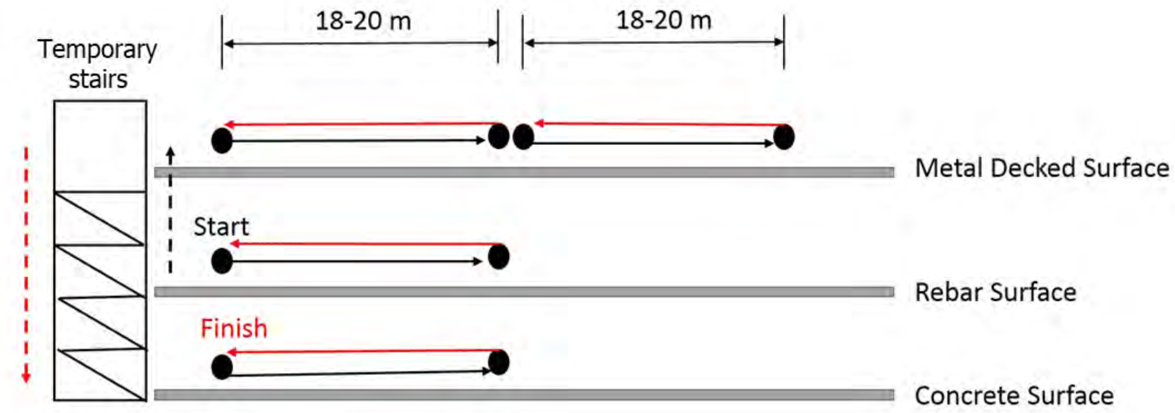


Figure 42. Predetermined path for the walking speed trials.

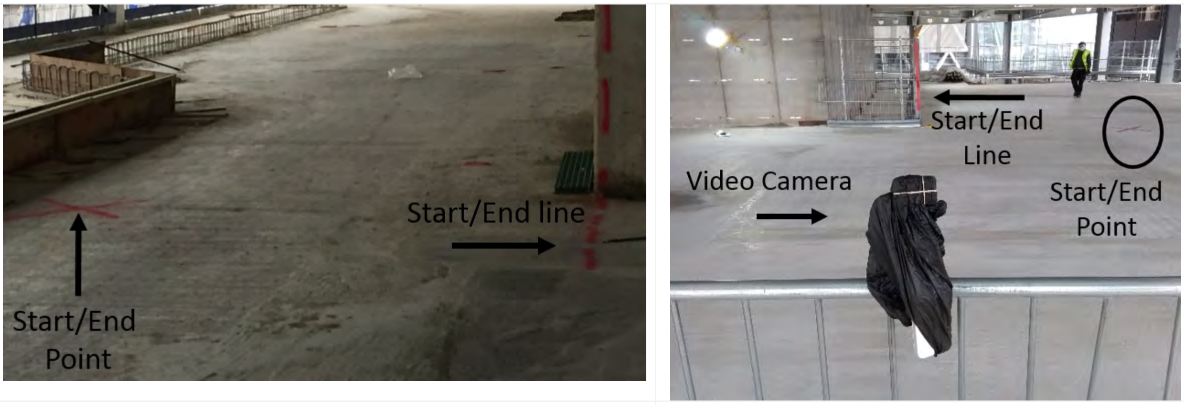
The procedures for the walking trial were as follows:

- the walking tracks would be closely located next to a temporary stair to be used in the trial for data collection
- participants take part one at a time over each leg of the course
- the first participant starts the first leg, the starting line being adjacent to the temporary stairs to be used in the trial. They walk along the REBAR floor surface in one direction a total of approximately 20 m past a finish line and wait
    - once the first participant has crossed the finish line, the second participant is released until all the participants have completed the first leg
    - each participant then repeats the exercise walking back past the start line
- as participants cross the start line (completing the second leg), they then travel up the temporary stairs (one at a time) to the metal decked level
- once they reach the METAL DECK section, the process is repeated. However, this time once they have completed the ALONG the decking leg (leg three), they do the ACROSS the decking leg (leg four)
    - once all participants have completed both legs (legs three and four), they repeat both legs going back to the start (legs five and six)
- as participants cross the end line of the metal (completing leg six) they then travel down the temporary stairs two levels to the concrete surface
- participants enter the temporary stairs one at a time and on instruction from a team member who ensures that no one else is on the stairs at the time. Their entry and exit of the stairs are monitored by synchronised video cameras
- once they reach the CONCRETE section, the process is repeated. Each participant individually walk along the CONCRETE floor surface in one direction (leg seven) a total of approximately 20 m past a finish line and wait until all participants have completed leg seven
    - each participant then repeats the exercise walking back past the start line (leg eight)
- as participants cross the start line (completing leg eight), they have completed the experiment and are free to go.

On each leg of flooring, the participants had to travel at least 18 metres (the longest available travel distance in one of the trials). As the participants travelled the length of floor surface twice, two travel speeds for each floor surface for each participant is determined. A minimum travel distance of 18 metres was considered a sufficient travel distance to mitigate for the effects of acceleration and deceleration and to gain a good average travel speed across each floor surface.

At the start of each leg, participants were placed at a starting location, marked by an 'X'. Participants were instructed to walk as fast as they can, WITHOUT RUNNING until they reached the 'X' at the other end. The actual start and end lines from which the data was actually recorded was indicated by red marks on the floor surface and adjacent wall. The exact travel distance was measured between these two lines and the travel time determined when the participant crossed each of the lines as recorded by two synchronised video cameras (as shown in Figure 43). The red cross was placed at least 2 metres from the start/end lines to allow participants to take a few steps allowing for start-up acceleration and slow-down deceleration. Participants were instructed to walk as fast as possible but NOT to run. They were reminded of the instruction at the start of each leg of the course.

Each participant was given a numbered badge which they wore throughout the trial. At the start of each leg, the team member controlling the start would call out the number which was recorded on the video. In addition, each participant entered their number into the questionnaire they completed after participation. Each walking leg of the experiment required three members of the research team: one to manage the waiting participants, one to control the start point and one to control the end point.

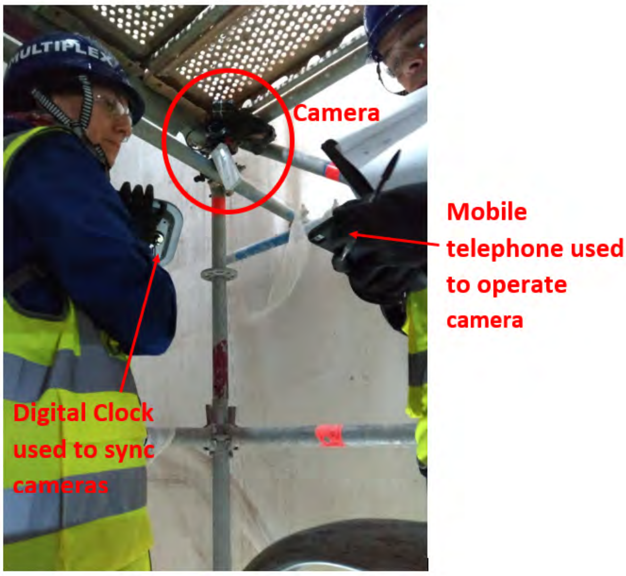


(a) Concrete surface showing 'start/end line' and 'start/end point'.

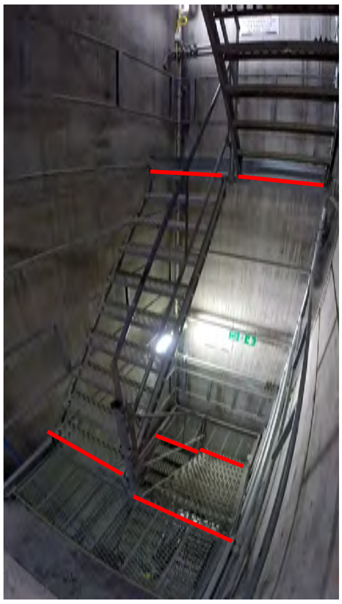
(b) Concrete surface showing 'start/end line', 'start/end point' and video camera.

Figure 43. Walking trial 'start/end line' and 'start/end point' locations on concrete surfaces with position of video camera relative to 'start/end line'.

The data capture on the stairs was undertaken in a similar manner. Synchronised video cameras were positioned at the top and bottom of the stairs (see Figure 44). Participants were instructed not to run down the stairs. Using the video cameras, their time of travel down the stairs was recorded. Unfortunately, as the stairs were in normal use, some of the data points could not be used as the trial participant's journey down the stairs was disrupted by a worker who was also using the stairs.



(a) Camera being set up on the stairs.



(b) Start / end line on the stairs.

Figure 44. Walking trial 'start/end line' and 'start/end point' locations on temporary stairs.

A very brief questionnaire was devised for the walking experiments. This consisted of the collection of simple demographic and experience data. Specifically, participant height, weight, age group and number of years of experience working on construction sites. Names of each worker were not collected, but the participant trial number was included in the questionnaire.

3.6.3 Specific details walking experiments

For each walking speed experiment, a site visit was required a couple of days prior to the experiment to enable the research team to familiarise themselves with the building, identify where the different floor types and stairs were, and identify suitable camera locations.

For each walking speed experiment, the following general timeline was followed.

- The day before the trial:
  - camera batteries charged, camera memories cleared and equipment packed.
- Day of the walking speed trial:
  - research team arrives to set up cameras for walking trials at 11:00
  - setup completed by 13:00
  - trials start at 14:00
  - trial completed by 15:00, start taking down cameras and tidying up
  - pack up completed and FSEG team leave the site at 16:00.

A total of five walking experiments were planned with an aim of generating at least 100 data points for each parameter measured. Each experiment aimed to involve about 20 workers in order to limit their downtime to about 30 minutes. However, as only a single type of temporary staircase was available for each trial it was unlikely that sufficient stair data would be collected for both types of stairs. Also, interruptions in the collection of stair data would result in the loss of data points. As a result, additional participants were recruited for the trials and worker involvement increased to about 60 minutes.

In total 152 workers participated in the five experiments, generating a total of 671 data points (see Section 4.8).

3.7 Ethics approvals

The proposed trial procedures and data-handling protocols were submitted to and approved by the independent University Research Ethics Committee (UREC). The UREC Chair granted approval in October 2016 (reference: Minute 16.1.5.7) (see Appendix 3).

3.8 Data analysis methodology

From the four full-scale evacuation trials, approximately 2,263 GB of video data was collected from the video cameras, representing over 268 hours of video footage:

- for Trial 1 at 100 Bishopsgate (14/02/17), 716 GB representing almost 85 hours of video footage was collected
- for Trial 2 at 22 Bishopsgate (28/02/17), 600 GB of video data was collected representing approximately 71 hours of video footage
- for Trial 3 at 100 Bishopsgate (04/10/17), 448 GB of raw video data was collected representing approximately 53 hours of video footage
- for Trial 4 at 22 Bishopsgate (16/10/17), 499 GB of raw video data was collected representing approximately 59 hours of video footage.

From the five walking speed trials approximately 607 GB of video data was collected from the video cameras, representing over 71 hours of video footage:

- for walking speed experiment 1 at 100 Bishopsgate (February 2017), 129 GB of video footage was collected representing almost 15 hours of video footage
- for walking speed experiment 2 at 100 Bishopsgate (May 2017), 85 GB of video footage was collected representing almost 10 hours of video footage
- for walking speed experiment 3 at 22 Bishopsgate (September 2017), 139 GB of video footage was collected representing almost 16.5 hours of video footage
- for walking speed experiment 4 at 100 Bishopsgate (October 2017), 152 GB of video footage was collected representing almost 18 hours of video footage
- for walking speed experiment 5 at 22 Bishopsgate (December 2017), 102 GB of video footage was collected representing almost 12 hours of video footage.

This represents an enormous amount of video footage from which the raw data had to be extracted. In order to extract the required data from the video footage, all the video had to be copied from the video cameras and transferred to a computer where it could then be edited and analysed.

To systematically and accurately extract data from the video footage required the development of a data dictionary which clearly and precisely defined the nature of the events to be identified and measured. In total four data dictionaries were defined, three for the evacuation trials and one for the walking speed experiments. Of the evacuation trials, these consisted of one for the response time data, one for the evacuation time data and one for the stair use data. For the walking speed experiments, which consisted of horizontal and vertical movement data, a single data dictionary was developed.

The data dictionaries for the evacuation trials consist of the following key terms:

The **evacuation time data dictionary** consists of three items:

- Alarm Activation Time (AAT): time at which the alarm can be heard to activate. As all the video cameras are synchronised this should be the same time on each camera
- Exit Time (ET): time at which the person is deemed to have exited. This is clearly defined for each exit point and can, for example, be the time at which the person's trailing leg is seen to

cross an exit line (for example the line marked by a door frame) or the time for the person to step off the stair (for example when the person's trailing foot is no longer on the base of the stair)
- Exit Count (EC): number of persons who have exited from the exit at a given ET.

Given the variety and complexity of activities that occur during the response phase, this was the most complex of the three data dictionaries and was developed iteratively as new behaviours were noted.

The **response phase data dictionary** consists of the following items:

- Alarm Activation Time (AAT): time at which the alarm can be heard to activate. As all the video cameras are synchronised this should be the same time on each camera
- Start of Activity Stage (SAS): time at which worker begins to undertake post-alarm activities such as begin to pack up tools, shut down equipment, etc.
- Supervisor Intervention Time (SIT): time at which a member of the management team or other worker intervenes with the worker under observation
- End of Response Phase (ERP): time at which worker begins to take purposeful evacuation movement towards the exit
- the number and nature of the activities that the worker was involved in during the ACTIVITY stage of the response phase. This consisted of ACTION and INFORMATION tasks:
    - ACTION TASKS consisted of the following types of activities (for a full list see Appendix 5):
        - remove tool belt: this is a common task undertaken prior to starting to evacuate. The task requires the worker to unbuckle/unclip their tool belt, remove the tool belt from their midriff and place it down on the floor
        - secure area: typically, the worker cannot leave the area until they have made it safe; for example, the glaziers cannot leave a pane of glass suspended over the edge of the building
        - collect tools or clothing: a common task undertaken prior to starting to evacuate involves the worker collecting or possibly putting on an item of clothing, such as a jacket, or collecting their tools to stow away
    - INFORMATION TASKS consisted of the following types of activities (for the full list see Appendix 5):
        - use mobile telephone: the worker is seen either making or receiving a telephone call. Typically, the worker is seen holding a mobile phone to their ear. Alternatively, the worker is seen operating the phone, for example sending a text
        - talk to others: the worker is seen engaging in conversation with other workers
        - receive instructions: the worker is seen communicating with a supervisor
- additional information: for each worker observed, the following additional information was collected:
    - gender
    - age group – the age is estimated to be in one of three age ranges: less than 20, 20–39 and 40+
    - pre-alarm activity – nature of work e.g. glazing, MEP, etc.
    - group status – whether the worker was isolated at the time of the alarm or in a group with other workers who were visible to them
    - supervisor/other worker intervention – whether someone intervened during the response phase and, if so, who and at what time.

The **stair usage data dictionary** was used to define how many people typically descended a flight of temporary stairs at any one time and, more importantly, how they maintained their interpersonal spacing. The entire run of temporary stairs was not clearly visible so, as part of the data collected, the section of stair being monitored for data collection was identified. The data collected consisted of the following:

Properties of the stair being monitored:

- stair location and stair type (dogleg/parallel and number of treads)
- location of stair section (e.g. between Level N and Level N+1, lower/upper flight)
- nature of stair flight (e.g. last flight, or first flight, or mid-flight, etc.).

The global observation measures:

- observation period, i.e. the total duration that the stair usage data was collected from the monitored stair section from the start of the alarm to the moment when the last worker stepped off the stair
- total number of people using the stair section during the observation period
- overall flow rate during the observation period.

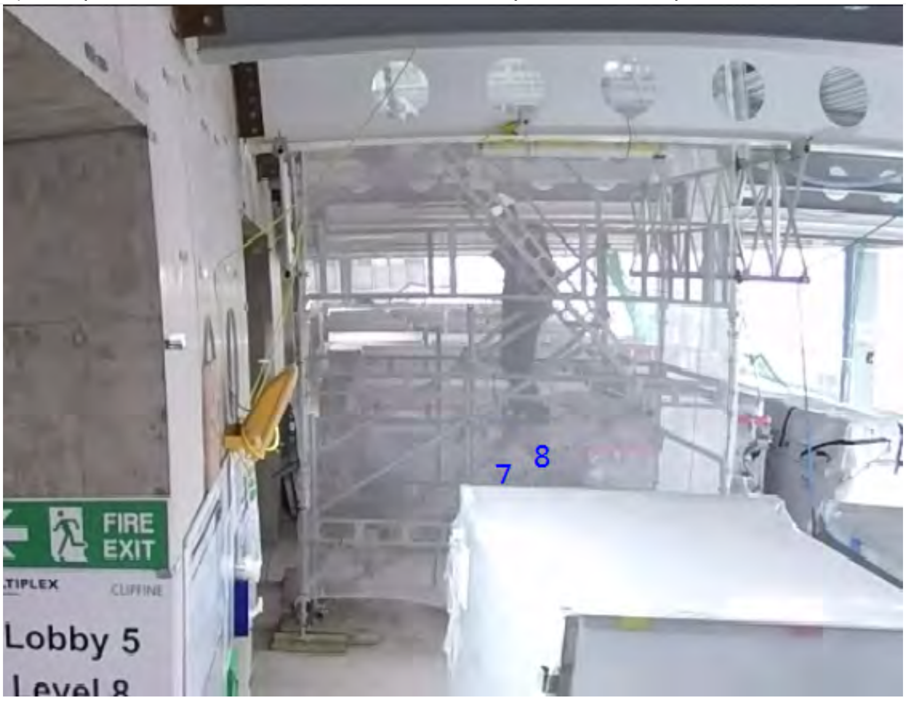
Behaviour of descending group and group spacing:

- A continuous stream of people moving on the flight are defined as a group if any two consecutive people are initially separated by fewer than five treads on the stair. If they are separated by five or more treads they are not considered to be a group as the distance between two consecutive people is so great that there is unlikely to be any interaction between them (see Figure 45).
- Measurements relating to groups:
    - group start time: this is the moment when the first group member steps on the top tread of the monitored section of stair
    - group end time: this is the moment when the last group member steps off the bottom tread of the monitored section of stair
    - number of people in a group: this is the number of people travelling on the monitored section of stair between the group start and end times
    - sampling of spacing measurement: a sampling of spacing measurement between group members is made when a group member enters or exits the monitored section of stair and there are at least two group members travelling on the monitored section of stair
    - spacing measurement: when a sampling of spacing measurement is made, the sampling time, the number of group members on the stair flight and the step location of each person are recorded. The step location of a person is defined as which tread their foot is in contact with. If the person is in contact with two treads at the same time, we define that they are located on the tread which is in contact with their foot bearing their body weight. The spacing (i.e. the number of empty treads) between any two group members on the section of stair is then calculated (see Figure 46).

Figure 45. An example of two workers descending on the stair who were not considered to be in a group as they are six treads apart.

(a) The person is in contact with both tread 8 and 9. Since his front foot bears his body weight on tread 8, his step location is tread 8.

(b) The person is in contact with tread 8 only, thus his step location is tread 8.



(c) The person is in contact with both tread 7 and 8. Since his rear foot bears his body weight on tread 8, his step location is tread 8.

Figure 46. Determining step location on stairs.

The **walking speed experiments dictionary** consists of the following items:

- For the walking on the flat trials:
    - type of surface
    - Start Time (ST): time at which the person's lead foot crossed the start line
    - End Time (ET): time at which the person's trailing foot crossed the end line.
- For the stair trials:
    - type of stair
    - location of the start line

- location of end line
- Start Time (ST): time at which the person's lead foot crossed the start line
- End Time (ET): time at which the person's trailing foot crossed the end line.

Given the limited number of video cameras, it is noted that the intention of the data collection and analysis was to focus on work activities associated, perhaps uniquely, to construction sites. Thus response times of staff involved in other activities such as working in site offices, in site cafes or in changing rooms were not included.

Once the data dictionaries were defined, data extraction could commence. The video analysis was performed using Adobe Premiere Pro CC 2018, a professional non-linear video processing software tool. Depicted in Figure 47 is the work environment in Adobe Premiere Pro with a person under investigation highlighted within a red circle and appropriate markers in green indicating various phases of that person's assembly process placed on the timeline. The analysis involved frame by frame examination of each video file. Each visible worker in a video file is examined separately. A marker is placed on the video timeline indicating the time when various events take place, e.g. AAT, SAS or ERP. The additional information, e.g. age, pre-alarm activity, for each worker could also be included on the timeline marker.

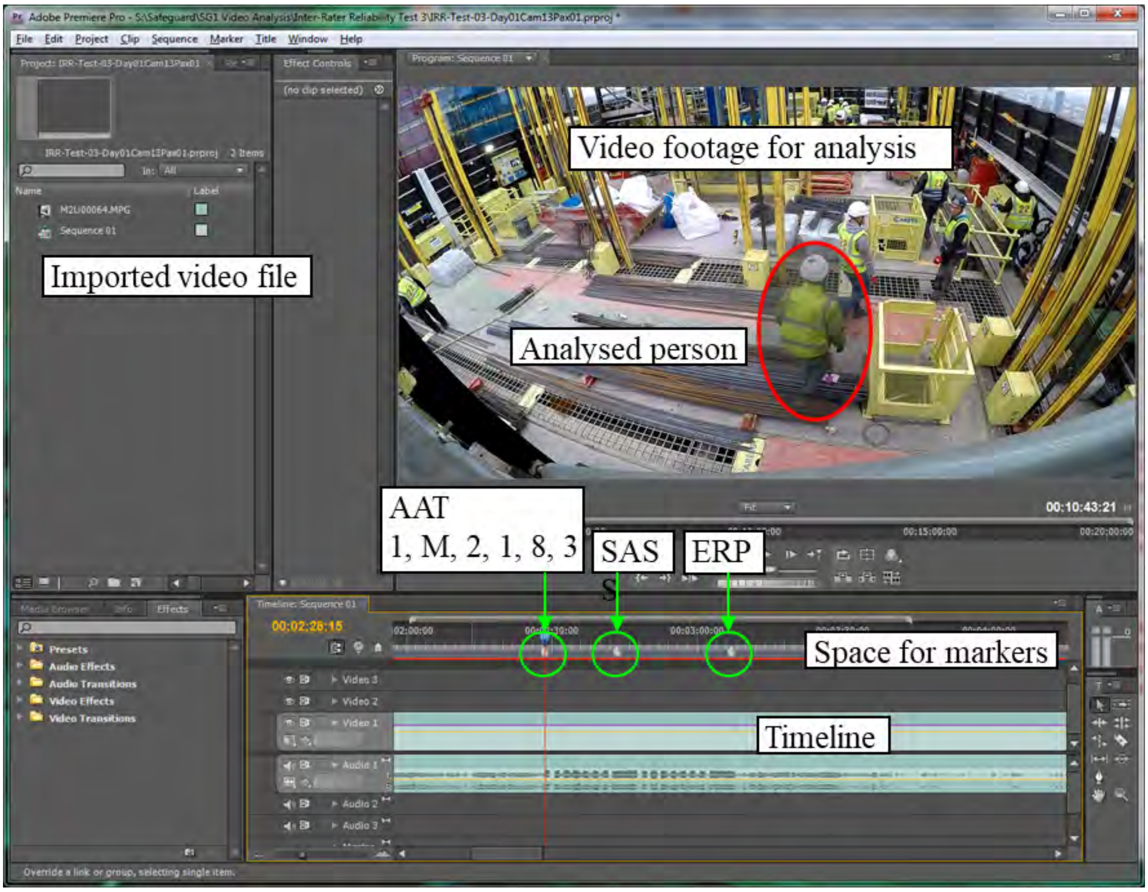


Figure 47. The work environment of Adobe Premiere Pro used for video analysis.

A computer program was developed to extract the data from Adobe Premiere Pro CC 2018 for each worker, analysed and stored as a text file that could be imported into commercially available software such as Microsoft Excel or Matlab for further analysis.

Two FSEG staff were used to analyse the video footage. Prior to the commencement of the video analysis process, the two staff were trained in the data analysis techniques. This included familiarity with the data dictionaries and how to identify the various elements from the data dictionary. Once trained, the analysts undertook an inter-rater reliability assessment to ensure that they could analyse the video footage accurately and consistently. Only once an acceptable level of performance was attained on the inter-rater reliability assessment could the video footage derived from the trials be processed. The inter-rater reliability assessment was an iterative process. Each analyst analysed 10 workers independently, selected from different parts of the construction site, and compared the results with the analysis of the other analyst. If the analysts did not achieve at least a 90% level of agreement, the differences were analysed, corrective measures were put in place and where necessary, the definition dictionary was updated. The inter-rater process was then repeated with a new batch of 10 workers until a level of agreement of at least 90% was achieved. The inter-rater reliability process for the first set of trials required two iterations to achieve a level of agreement of over 90%.

On completion of the inter-rater reliability tests, two analysts commenced the analysis of all video captured during the evacuation trials. This was a lengthy process that took approximately four months to complete for Trial 1 (100 Bishopsgate) and generated 106 worker response times, approximately one month for Trial 2 (22 Bishopsgate) generating 30 response times, approximately three months to complete the video analysis for Trial 3 (100 Bishopsgate) generating 52 response times and approximately four months to complete the video analysis for Trial 4 (22 Bishopsgate) which produced 87 response times.

When all video from each trial had been analysed, the RT distributions for each could be determined as shown in Figure 48. RT distributions for the entire construction site could be constructed or specialist RT distributions based on parameters such as starting location or pre-alarm activity could be constructed.

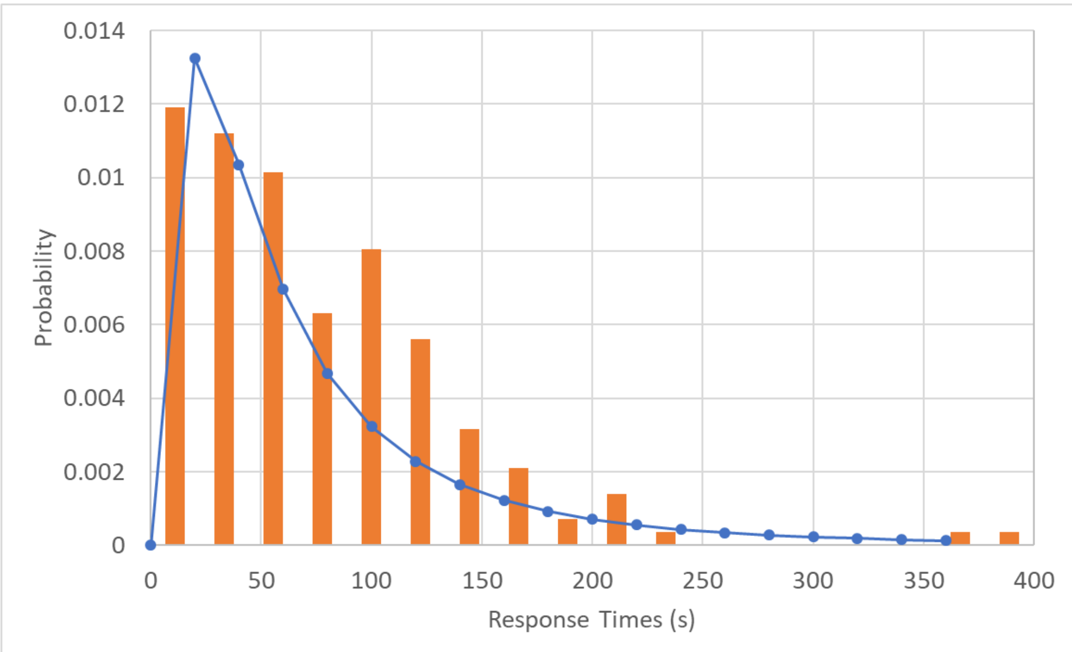


Figure 48. Example distribution of response times from evacuation trials.

In addition some 920 exit times were extracted for the four full-scale evacuation trials (see Section 4) and some 545 walking speed data points were extracted from the walking trials (see Section 4.8).

4 Data analysis

In this section the data from the four full-scale evacuation trials and the five walking speed experiments are analysed. The data-set generated from these nine trials involving 1,072 participants incorporates around 2,200 data points, extracted from 3 GB of video data, and information from 61 worker questionnaires. The data-set involves:

- the evacuation of 920 participants
- the measurement of 920 exit times
- the measurement of 275 response times
- walking experiments involving 152 participants
- the measurement of 545 walking speeds over four different types of surfaces
- the measurement of 126 stair walking speeds on two different types of stairs
- the measurement of 59 ladder speeds
- the measurement of 203 interpersonal distances on temporary stairs.

The analysis of this data is intended to produce generalised distributions for response times, walking speeds, stair speeds and ladder speeds. Combined, this information can be used to calibrate evacuation models and to provide a validation data-set. This section describes the work undertaken as part of project Task 3 to address project Objectives 1–3.

In reviewing the results of this analysis, a number of terms will be used to describe the nature of the activity that workers are engaged in. These are defined as follows:

- **Glaziers**: these are the workers that are installing panes of glass or windows into the building façade. The glaziers work in teams involving several workers including crane operators who lower the pane of glass down from the floor above. There may also be workers in cherry pickers who are essentially outside the building manoeuvring the pane of glass into place.

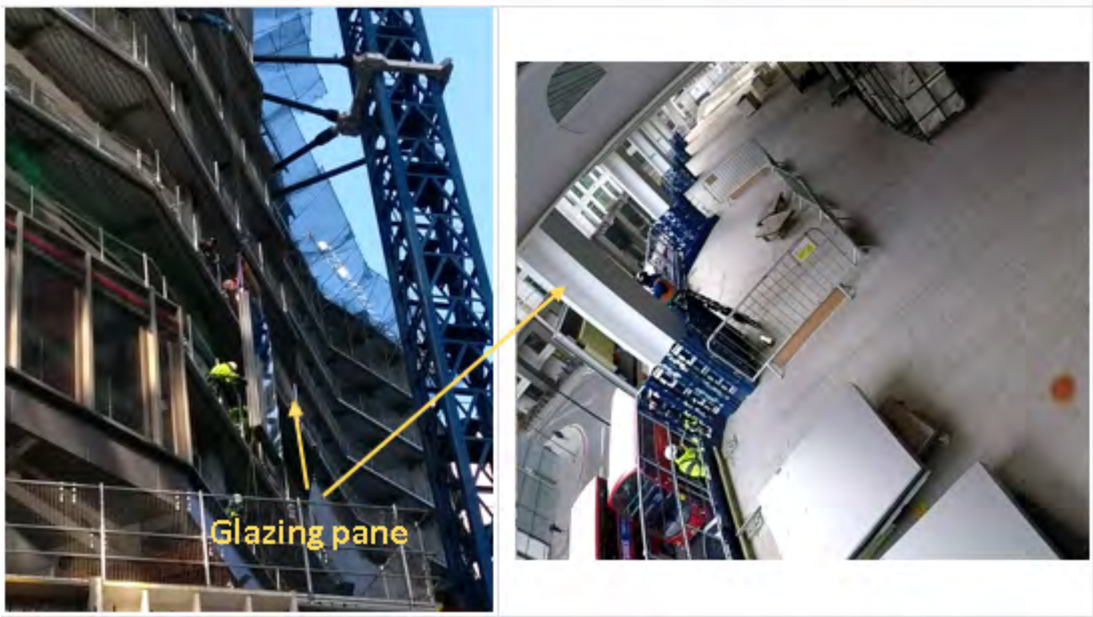


Figure 49. Glaziers installing glass pane at 100 Bishopsgate.

- **Workers at height**: these are workers that are engaged in activities above the floor slab. They may be perched on a tower or up a ladder.

- **MEP**: these are workers who are installing mechanical, electrical or plumbing on the construction site. This is work commonly being undertaken on the lower floors where the concrete floor surface has finished being constructed.
- **Rebar installers**: these are workers engaged in installing rebar on the metal decking prior to a concrete pour (see Figure 50).

Figure 50. Worker installing rebar.

- **Isolated workers:** these are workers who are alone in a part of the building and cannot see other workers from their current position (see Figure 52).
- **Crane supervisors**: these are workers who are directing and aiding the crane driver and are in radio contact with the crane driver, directing them. The crane supervisors also hook up and unhook the crane's load. The crane supervisor is responsible for the safety of all workers in the vicinity.

Response times for staff involved in other activities, such as working in site offices, staff located in site cafes or in changing rooms were not considered.

4.1 Trial 1: Results from the full-scale evacuation

In this section results from the first full-scale evacuation trial conducted in 100 BG on 14 February 2017 are presented and discussed. At the time of the evacuation, the building consisted of 19 core levels with 12 floors in various stages of completion. In total there were 184 workers on site at the time of the evacuation. Detailed quantitative analysis of the nature of the RT distributions derived from these trials including a comparative analysis of the data derived from all four trials and any possible generalisations derived from the combined data is presented in Section 4.6. In this section we focus on exploring the nature of the data generated from this trial and identifying factors which may have influenced the data.

The construction site made use of two emergency alarm sirens and the use of flashing lights located at the exit of the core onto outer floors. In the event of an emergency, the first alarm would sound alerting the main building, the ground level, basement and welfare areas of the immediate need to evacuate. This alarm would also alert workers in the slipform of the possibility that they may have to evacuate. However, the slipform workers were instructed not to commence their evacuation until the sounding of the second alarm which confirms the need for them to commence their evacuation.

During the trial the second alarm was sounded within 10 s of the first alarm. More than 60% of the workers in the slipform ignored the first alarm (i.e. did not disengage from their pre-alarm activities) and so the second alarm is considered to be the main cue for workers to start the evacuation.

4.1.1 Response times extracted from Trial 1

From the video footage of the trial, 184 workers were recorded as exiting the building. In addition, 106 response times were extracted from the video footage, of which 80 response times were for workers above ground level, with 20 in the jumpform. There were 26 response times recorded from workers on the ground level; however, exit times were not extracted for these workers as they did not pass through one of the identified exit points.

Of the 184 workers on site, response times were captured for over half (58%) the workforce as shown in the graph in Figure 51. For the slipform workers, the response time is measured from the second alarm.

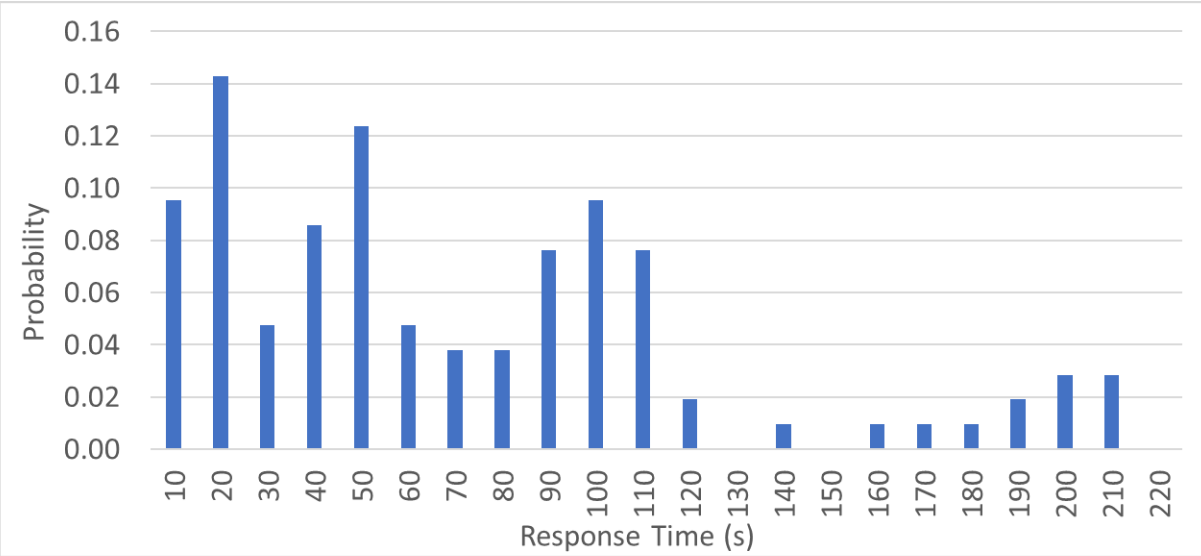


Figure 51. Response time distribution recorded from workers at 100 BG during Trial 1 (slipform measured from the second alarm).

Overall, the RT distribution appears to be lognormal in appearance (see Figure 51). The first worker to respond to the alarm in the main part of the building (excluding the ground floor) did so after 8.8 s while the last worker responded after 204 s. The first worker to respond was installing rebar while the last worker to respond was a glazier. In the slipform, the first worker responded to the (second) alarm after 0.16 s with the last worker responding after 51 s. The workers in the slipform were dismantling the jumpform following a concrete pour. The last worker to respond to the alarm, a glazier, did so after 204 s.

Finding 1.1: Overall, the response time distribution for the high-rise construction site observed in Trial 1 resembles a lognormal curve, with minimum response time of 0.16 s and maximum response time of 204 s. Response time data points were collected from 80 workers located up to Level 15 and 20 workers in the slipform located at Level 20.

The overall RT distribution can be divided into groups based upon common tasks being carried out by the workers. Table 9 presents a list of seven common tasks along with the number of workers performing those tasks and a description of the RT distribution generated by each group of workers (excluding workers on the ground floor). Excluding those in the slipform, the mean response time varies from 40 s for MEP workers to 195 s for glaziers, with those installing rebar responding in 53 s, crane supervisors responding in 64 s, those working at height responding in 98 s and isolated workers responding in 149 s.

Finding 1.2: The nature of the pre-alarm activity that the worker was involved in (i.e. the nature of the work associated with the identified work group) will impact how rapidly they respond to the alarm, with MEP workers having the shortest mean response time (40 s) and glaziers having the longest mean response time (195 s). Isolated workers also can take a long time to respond to the alarm (149 s).

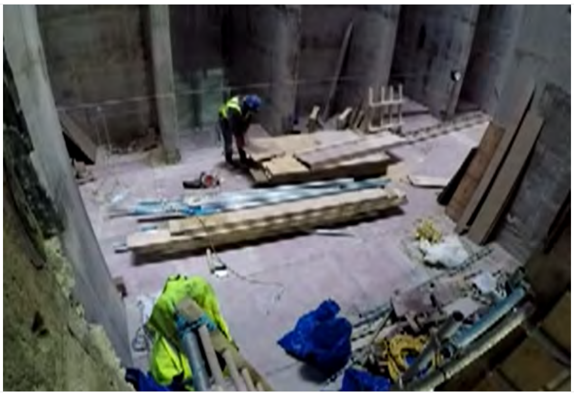
As can be seen from Table 9, the glaziers take far longer to disengage than any other group of workers, with an average of 195 s. Even the quickest response time from a glazier is some 36 s longer than the next largest response time (that of an isolated worker).

The reason that the glaziers took so long to respond to the alarm was because they were involved in a task which they had to make safe prior to starting their evacuation. At the time of the alarm, the glaziers were installing a window pane on a lower floor. This involved a large glazing unit being suspended from a crane outside the building with several workers also suspended outside the building in cherry pickers. Clearly, the task had to be completed or made safe before the entire team could start their evacuation. It is noted that had the alarm occurred at another time, the glaziers could have been involved in work that could easily be stopped resulting in much shorter response times. It remains to be seen if in the other evacuation trials glaziers are engaged in non-critical work, and if so, what their response times will be.

Finding 1.3: The long mean response time for the glazier work group was the result of particular activities they were involved with at the time of the alarm that had to be made safe prior to evacuating. While this may appear to have been exceptional circumstances, if glaziers are on site during an alarm it is possible that they will be involved in these types of activities. In formulating a generalised response time distribution to represent the response of construction site workers, it is reasonable to include these longer response times, especially if the data is to be used in life safety assessments.

Apart from the glaziers, who were involved in work that must be made safe before leaving, isolated workers have the next longest response times. Two isolated workers were observed with an average response time of 121.2 s. Being isolated and not receiving the additional cues of seeing other workers respond to the alarm can result in very long response times. While these difficulties can be compounded if the worker is wearing ear protectors, in these instances the workers were not wearing ear protectors.

Consider as an example an isolated worker located in the core, captured by camera15. As the fire alarm sounds, the worker is engaged in a work task in the core at Level 15 (see Figure 52a). The task he is involved in is not one that must be made safe prior to starting his evacuation nevertheless, he continues in his activities for the next 44 s, ignoring the alarm, which can be clearly heard on the video, and calls from fellow workers who are yelling, “fire alarm”. After 44 s, a supervisor comes into view and yells down to the worker to “evacuate”, “fire alarm, out, out, out” (see Figure 52b). After another 4 s (48 s after the alarm), the worker disengages from his pre-alarm activities and begins to undertake a number of ACTION tasks involving detaching the safety line, removing his safety harness and removing his tool belt (see Figure 52c). These tasks take 45 s to complete, at which point he starts to climb up the ladder, 93 s after the alarm sounded (see Figure 52d). It is quite possible that this worker would have continued with his pre-alarm activity for several minutes or longer had it not been for the staff intervention, endangering not only himself but also his colleagues/firefighters who may need to search for him. The supervisor also stays with the worker until he leaves and, after the worker leaves, the supervisor goes down to the level at which the worker was working to check the scene and begins to leave 105 s after the sounding of the alarm, 61 s after engaging with the worker. Clearly, during this lengthy engagement, the supervisor is not able to alert others.



(a) Isolated worker in core on Level 15 at the sounding of the alarm.

(b) Supervisor arrives after 44 s and instructs worker to evacuate.

(c) Worker had disengaged from pre-alarm activity and is releasing his safety line (59 s after alarm).

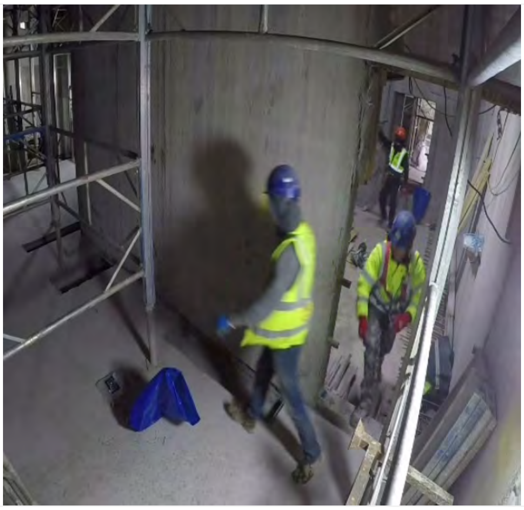
(d) Worker begins his evacuation movement phase 93 s after the sounding of the alarm.

Figure 52. Isolated worker delaying his response to the alarm and only disengaging on intervention from supervisor.

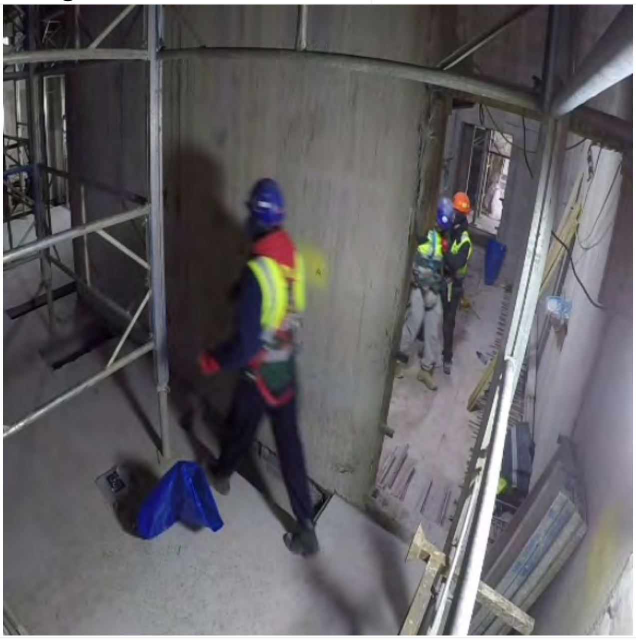
Through the video analysis process, it was clear that many workers did not respond to the sound of the alarm but rather only disengaged from their pre-alarm activity after another worker or a supervisor instructed them to leave. Of the 80 response times collected from above the ground floor, 58% (46 workers) only disengaged from their pre-alarm activity after a supervisor intervened. Thus it is not only isolated workers that rely on supervisor intervention to start the evacuation process and reduce response times.

As an example of supervisor intervention where the work is not isolated, consider the activities of a group of MEP workers on Level 14 in the core, captured by camera14. The workers, out of direct view of the camera, have continued to work through the alarm. Not only can the alarm be clearly heard at this location, but there are other visual cues such as the sight of other workers evacuating (see Figure 53a). A passing supervisor (black clothing, red helmet) sees that this group of three workers have not responded to the alarm and starts to yell out orders to them to evacuate (Figure 53b). As the workers do not appear to be responding, or not responding fast enough to the supervisor’s commands, the supervisor is seen physically encouraging a worker to leave (see Figure 53c). Some 28 s after the supervisor arrived, three workers have responded and left the area. The last person to leave the area has an estimated response time of 62.8 s.

(a) MEP workers evacuating past other workers who are still engaged in work activities (out of view of the camera). A supervisor (in black with red helmet) is approaching the area.



(b) Supervisor is seen and heard yelling at workers to stop work and get out.



(c) Supervisor is physically encouraging worker to leave.

Figure 53. Supervisor intervening to encourage non-isolated workers to evacuate.

Furthermore, the 46 workers who responded after the alarm and after a supervisor intervention had a mean response time of 61.8 s, while the 34 workers who responded without needing supervisor intervention did so on average after 75.9 s. So workers who received two stimuli – alarm and supervisor intervention – tended to react 18% quicker than those who only received a single stimuli – the alarm. So without the supervisor intervention, it is reasonable to assume that the response time of those who received the intervention would have been at least as long as those who responded only to the alarm and perhaps depending on the circumstances (e.g. isolated workers) significantly longer.

Finding 1.4: The majority of workers (58%) in Trial 1 required some form of supervisor intervention to encourage them to disengage from their pre-alarm activities and start engaging in evacuation

activities. Without these interventions, the response times of the workers are likely to have been much longer. This highlights the importance of supervisors in reducing the response times of workers on construction sites. The analysis also suggests that had there been fewer supervisors (or if the supervisors did not do their job appropriately) it is likely that there would have been more workers with longer response times, adversely affecting the overall evacuation time distribution and conversely, had there had been additional (assertive) supervisors, response times are likely to have been reduced. It is not clear how significant an impact this would have on the overall evacuation time.

In contrast to the glaziers and isolated workers, the workers in the slipform were the quickest to disengage from their pre-alarm activity with the lowest minimum and maximum response time of any group of workers (irrespective of whether measured from alarm 1 or alarm 2). However, it is not clear why these workers responded so rapidly. It could be due to the nature of the work they were engaged in. As described in Section 3.3.1 these workers in the slipform were engaged in activities to reduce the size of the slipform. So rather than being engaged in time-critical work, such as erecting rebar just prior to a concrete pour, they were removing parts of the slipform infrastructure, including outer walls. This work may not have appeared time-critical to the workers and so they were more prepared to rapidly disengage from this activity and start their evacuation. Another possibility could be that the workers realise the difficulty of exiting the slipform (climb internal ladders to get to the top deck and then descend down a single-lane hanging stair onto the single-lane scaffold stair) and so are prepared to leave as soon as possible to avoid being caught in congestion. Furthermore, to a certain extent, the workers in the slipform were primed to commence their evacuation by the sounding of the first alarm which sounded some 10 s before the second alarm.

Table 9. Summary of response time distributions split into common tasks for Trial 1 (excluding 26 workers on the ground floor).

Task	Minimum Response Time (s)	Maximum Response Time (s)	Mean Response Time (s)	Standard Deviation	Number of Workers	Number of Supervisor Interventions
Overall*	0.2	203.8	65.0	54.6	79	46
Glaziers	184.6	203.8	195.4	7.4	8	3
Working at Height	96.8	100.2	98.2	1.3	4	1
Isolated Workers	92.2	150.3	121.2	22.4	2	1
Installing Rebar	8.8	106.7	52.6	33.0	18	11
Crane Supervisors	34.3	96.5	64.3	23.0	16	14
MEP	10.3	102.2	40.0	28.0	12	5
Slipform Alarm 1	7.7	64.8	42.2	17.8	20	11
Slipform Alarm 2	0.2	50.7	28.9	16.4	19	4

*: Measured from Alarm 2.

Given that the response times for the slipform workers were relatively fast compared to the other workers and given that they were in a somewhat unique and isolated situation and that they represent the largest group of workers for which response times were collected (20 of the 80 response times or 25% of the response times and 11% of the population that evacuated), it was considered appropriate to separate the response time of these workers from the general population and investigate the distribution separately, to determine if the distribution had any features that distinguished it from the distribution for the rest of the building. The RT distribution for the workers in the slipform is presented in Figure 54 while the RT distribution for the remainder of the population is presented in Figure 55.

For the rest of the building, the minimum, maximum and average response times are 8.8 s, 203.8 s and 65.0 s respectively with standard deviation of 54.6 s.

Apart from the obvious difference in the mean and maximum response times for the two distributions, their general appearance appears to be significantly different, with the distribution for the main part of the building (in Figure 55) resembling the typical lognormal distribution and the distribution for the slipform resembling more of a normal than a lognormal distribution. Using the Shapiro-Wilks test of normality, the slipform produced a p-value of 0.078; since this is larger than 0.05 we can conclude that the RT distribution from the slipform follows a normal distribution.

Finding 1.5: The data from Trial 1 suggests that workers located in the formworks appear to respond relatively quickly compared to those in the main part of the building. It is noted that the work undertaken in the formworks at the time of the evacuation was non-critical in nature which may have impacted the response behaviour of the workers.

Furthermore, the response time distribution for workers in the main part of the high-rise construction site appears to follow the usual lognormal distribution, with minimum response time of 9 s, maximum response time of 204 s and a mean response time of 76 s. However, the response time distribution for workers in the formworks does not appear to follow a lognormal distribution typical of most response time distributions but appears to be defined by a normal distribution with minimum response time 0.2 s, maximum response time 51 s and a mean response time of 29 s.

If these observed differences can be substantiated by data from the other trials, it suggests that the response time distribution for high-rise construction sites cannot easily be described by a single distribution, but requires two distributions to describe the response behaviour of the two distinct populations.

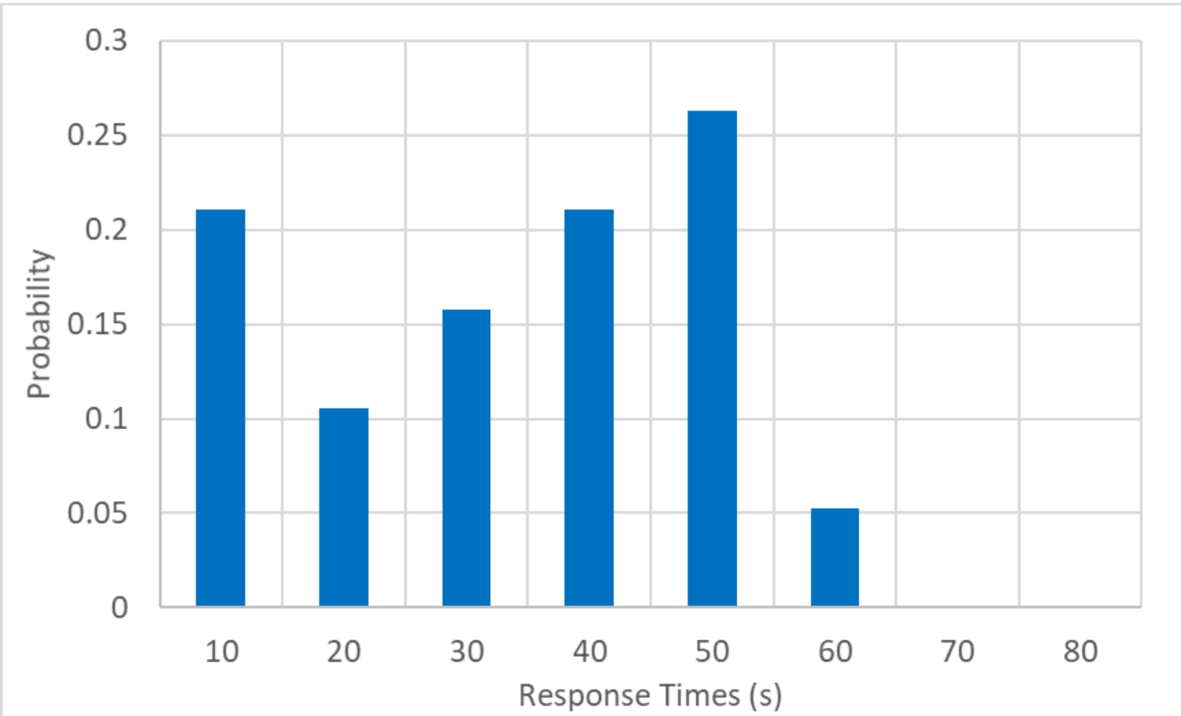


Figure 54. Response times for workers in the slipform during Trial 1 (measured from alarm 2).

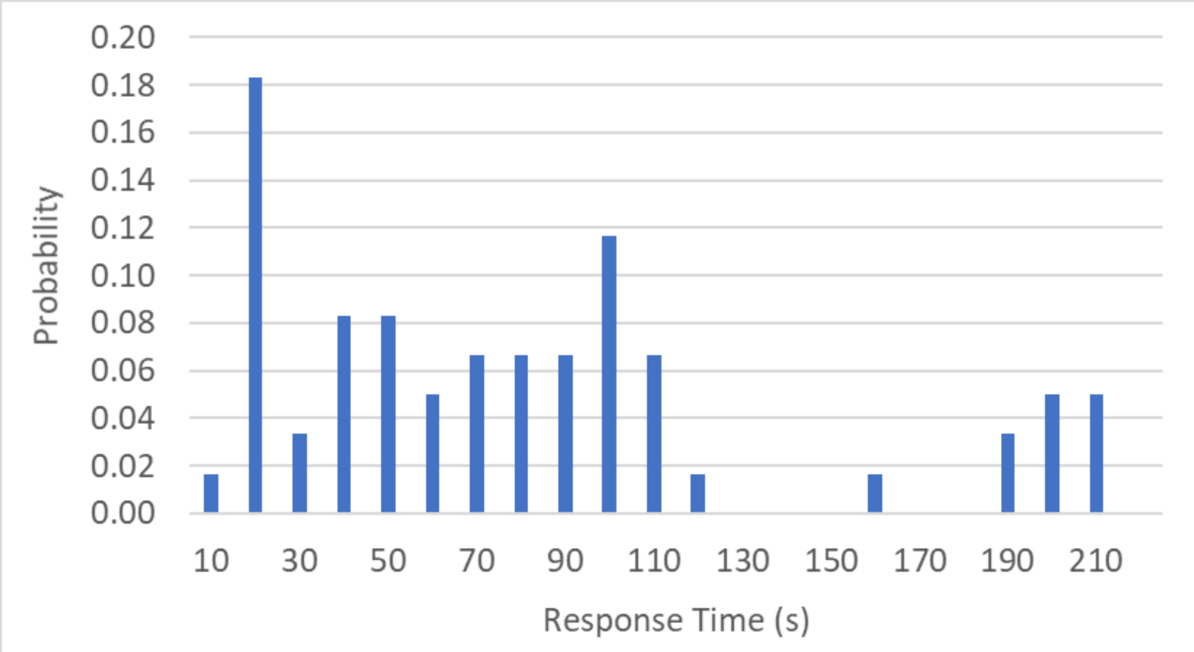


Figure 55. Response times for workers not in the slipform during Trial 1.

4.1.2 Questionnaire data for Trial 1

The questionnaire (see Appendix 2) was completed by only 32 (30 completed the paper questionnaire and two workers completed the online survey) of the 184 workers who evacuated, representing only 17% of the population. Many of the workers simply refused to fill in a questionnaire. Of the 32 completed questionnaires, 26 were completed in English and six in Romanian. A number of the 30 paper questionnaires had missing data where the worker had either not finished the questionnaire or had skipped questions.

It was noted that the data collection setting was not conducive to gaining participation, canteens being a place and breaks being an interval where workers were often engaged in other activities or wished to rest, and the questionnaire was too long to be completed within the time period workers were willing to give up. As a result of this trial, the questionnaire was shortened and simplified for Trial 2 (see Section 3.5) reducing the estimated time for completion from 20 minutes to around 5 to 10 minutes.

As there was insufficient data returned from these questionnaires to conduct a meaningful statistical analysis, the data from this trial was combined with the data from the other trials and analysed in Section 4.5.

4.1.3 Total evacuation time data for Trial 1

The first worker was recorded as exiting the building 41 s after the alarm was sounded and the final worker was recorded as exiting the building 12 min 46 sec after the alarm sounded. The average exit flow achieved in this trial was 0.25 p/s. The exit curve for the building is depicted in Figure 56.

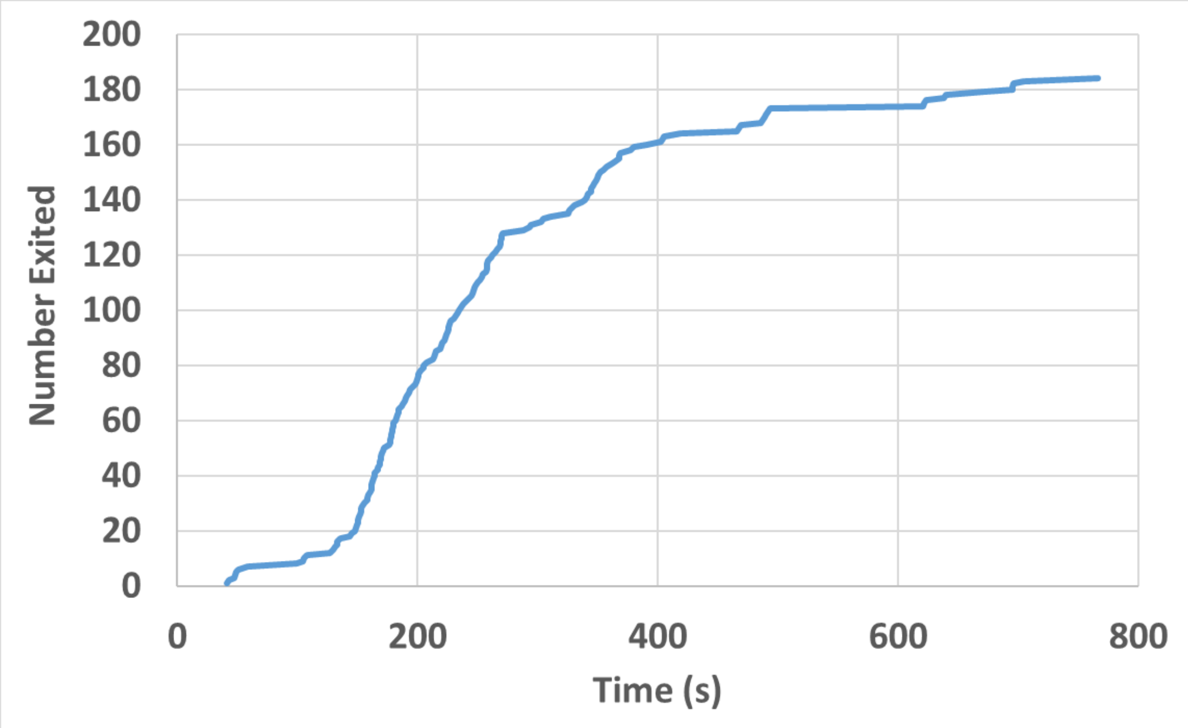


Figure 56. Exit Arrival curve for workers above ground level at 100 Bishopsgate during Trial 1.

Unfortunately, there were not sufficient cameras to monitor the entire construction site. Therefore not every floor was monitored. With the exception of the slipform, 100 BG had three exit routes from each level (the three temporary stairs, see Figure 5). While the top and the bottom of each exit route was monitored with a video camera, it was not possible to monitor the stair entry points on each floor as well as obtain response times of individual workers as there were insufficient video cameras to completely cover the entire building. Thus from the data collected, it is not possible to obtain the approximate starting floor location for most of the 184 workers that exited. While response times for 80 workers (above ground) were collected, and hence the starting location of these workers is known, the starting location of the other 100 workers is not known. Efforts were made to estimate the location of these workers through discussion with Multiplex management, but this could not resolve the location of individuals down to a floor. Without reliable information relating to the starting location of each worker, it will not be possible to establish a validation data-set from this trial.

4.1.4 Ladder ascent/descent speeds extracted from Trial 1

It is common for the entry point of a temporary scaffold dogleg staircase to not align with the floors of the construction site, resulting in the need to have a ladder to connect the entry point of the temporary staircase to the level of the floor. In one instance at 100 BG, it was necessary to use a long ladder to realign the temporary stairs with the floor levels. This occurred at Level 2 in the West temporary scaffold staircase and required a ladder of 4.5 m in length (see Figure 57).

This ladder was monitored so that the speed of workers ascending and descending the ladder could be determined. The speed is determined using the travel times and the travel distance. The travel distance on the ladder is approximated by the vertical distance between floors. As the distance between floors is quite long (see Figure 57), the ladder is virtually vertical and so the distance between floors is a good approximation for the travel distance on the ladder.

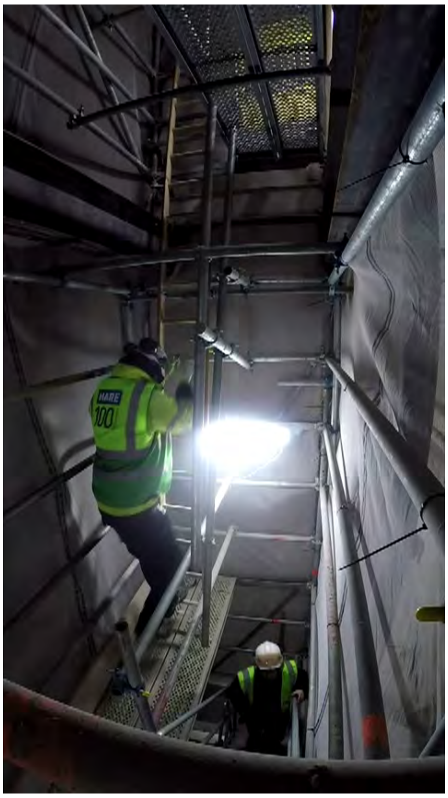


Figure 57. Ladder in slipform of Trial 1 used for ladder speed analysis.

In total, travel times for 59 workers were collected: 57 descending the ladder and two workers ascending the ladder. The speed data is presented in Table 10 together with the stair speed based on Fruin data [61]. As can be seen, the average ladder speeds are considerably smaller than the average Fruin speed (based on middle-aged walkers), with the average descent speed being 64% of the descent stair speed and the average ascent speed being 67% of the ascent stair speed.

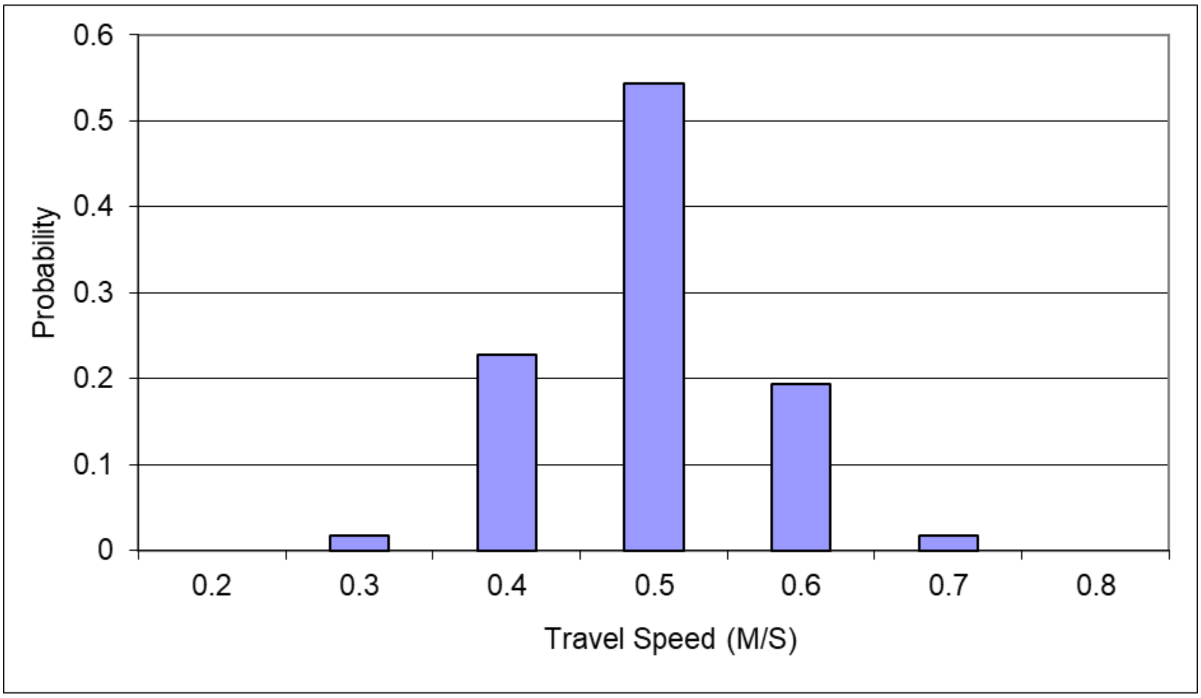


Figure 58. Ladder descent speed derived from Trial 1.

Table 10. Ladder and stairs ascent and descent speeds.

	Ladder descent m/s	Ladder ascent m/s	Stairs descent average (Fruin) m/s	Stairs ascent average (Fruin) m/s
Min	0.29	0.39	Male 51–80 0.53	Male 51–80 0.51
Average	0.45	0.42	Male 30–50 0.70	Male 30–50 0.63
Max	0.61	0.44	Male 17–29 1.01	Male 17–29 0.67

Key Finding 1.1: Ladder ascent/descent speeds – Ascent/descent speeds for workers on ladders have been determined from data derived from 59 workers in Trial 1. Average ladder ascent/descent speeds are considerably slower than the average speed attained on standard building stairs. The average descent speed on ladders (0.45 m/s) is 64% of the descent stair speed (0.7 m/s), while the average ascent speed on ladders (0.42 m/s) is 67% of the ascent stair speed (0.63 m/s). It should be noted that the ladder data has limitations due to the relatively small number of data points collected from the trial, especially for the ladder ascent (two data points).

4.1.5 Stair usage data from Trial 1

No stair usage data was extracted from Trial 1.

4.2 Trial 2: Results from the full-scale evacuation

In this section results from the second full-scale evacuation trial conducted in 22 BG on 28 February 2017 are presented and discussed. At the time of the evacuation, the North Core was populated with the jumpform at Level 14, with 13 core levels completed (or under construction) and no floors completed or under construction. In total there were 46 workers on site at the time of the evacuation: 43 located in the North Core and three in the South Core. Detailed quantitative analysis of the nature of the RT distributions derived from these trials including a comparative analysis of the data derived from all four trials and any possible generalisations derived from the combined data is presented in Section 4.6. In this section we focus on exploring the nature of the data generated from this trial and identifying factors which may have influenced the data.

4.2.1 Response times extracted from Trial 2

From the video footage of the trial, 46 workers were recorded as exiting the building: 43 from the North Core and three from the South Core. In total 30 response times were extracted from the video footage of the workers in the jumpform of the North Core.

At the time of the alarm the only work being undertaken on the construction site was in the jumpform, where steel rebar was being installed in preparation for a concrete pour. The first worker responded to the alarm 12.2 s after the alarm sounded, with the last worker to respond responding after 114.7 s, with a mean response time of 55.6 s and a standard deviation of 23.4 s. There were two supervisors present in the jumpform at the time of the alarm. They alerted workers of the need to evacuate and then self-evacuated without waiting to check that the jumpform was clear.

The RT distribution for the jumpform is presented in Figure 59. Clearly, the distribution does not resemble the typical lognormal distribution found in most RT distributions, but appears to be more of a normal distribution.

The RT distribution for the jumpform workers more closely resembles the distribution for the jumpform workers in Trial 1 (see Figure 54) than the distribution for the rest of the building in Trial 1 (see Figure 55). However, a significant difference between the two formwork RT distributions is that, in Trial 2 (Figure 59), the workers have a longer response time, with an average of 55.6 s compared with those in Trial 1 (Figure 54) who have an average response time of 28.9 s (measured from alarm 2, or 42.2 s measured from alarm 1). Nevertheless, the average response time for the workers in the formworks of Trial 2 (55.6 s) is considerably quicker (42% quicker) than the average response time for the workers in the rest of the building in Trial 1 (78.5 s).

Finding 2.1: The response time distribution for Trial 2 workers located in the formworks appears to be defined by a normal distribution with a minimum of 12 s, a maximum of 115 s and a mean response time of 56 s. Unlike in Trial 1, it is noted that the work undertaken in the formworks at the time of the alarm was critical, which may have impacted the response behaviour of the workers.

The difference in response time distributions for the frameworks and the rest of the building observed in Trials 1 and 2 supports the view that the response time distribution for high-rise construction sites cannot easily be described by a single distribution, but may require two distributions to describe the response behaviour of the two distinct populations.

An explanation for the longer response times for the formwork workers in Trial 2 compared to those in Trial 1 concerns the differences in the nature of the work being conducted within the formworks. In Trial 2 the workers in the formwork were installing rebar ahead of a concrete pour, which is considered time-critical work, while in Trial 1 the workers were dismantling the formwork, which is considerably less time-critical. Thus the nature of the work in Trial 2 resulted in the workers being more engaged in their tasks, resulting in the longer response times. While both types of work can be expected to be conducted in frameworks, they can result in very different response times from the workers. Furthermore, unlike the work of other groups e.g. the glaziers, it is unlikely that both types of work would be conducted at the same time and so the two distributions may be considered to be at either end of the response time spectrum for workers in frameworks – excluding the work associated with concrete pours which is expected to result in the longest response times.

Finding 2.2: While the response times for the workers in the formworks in Trial 2 are longer than those in Trial 1 (mean response time 56 s compared with 29 s or 93% longer), this may be explained by the time-critical nature of the work in Trial 2 (installing rebar ahead of a concrete pour) compared to Trial 1 (dismantling the formwork). This supports the view that the nature of the work that the worker is engaged in at the time of the alarm will determine the speed of their response.

Finding 2.3: The response time distribution for the workers in the formworks in Trial 1 and Trial 2 may define either extreme of response time distributions for this region of the building, with Trial 1 representing the 'fast end' and Trial 2 representing the 'slower end'. Given the nature of the work conducted in the formworks, both types of activity are unlikely to occur at the same time. However, it should be noted that work associated with concrete pours is likely to result in even longer response times than those for Trial 2.

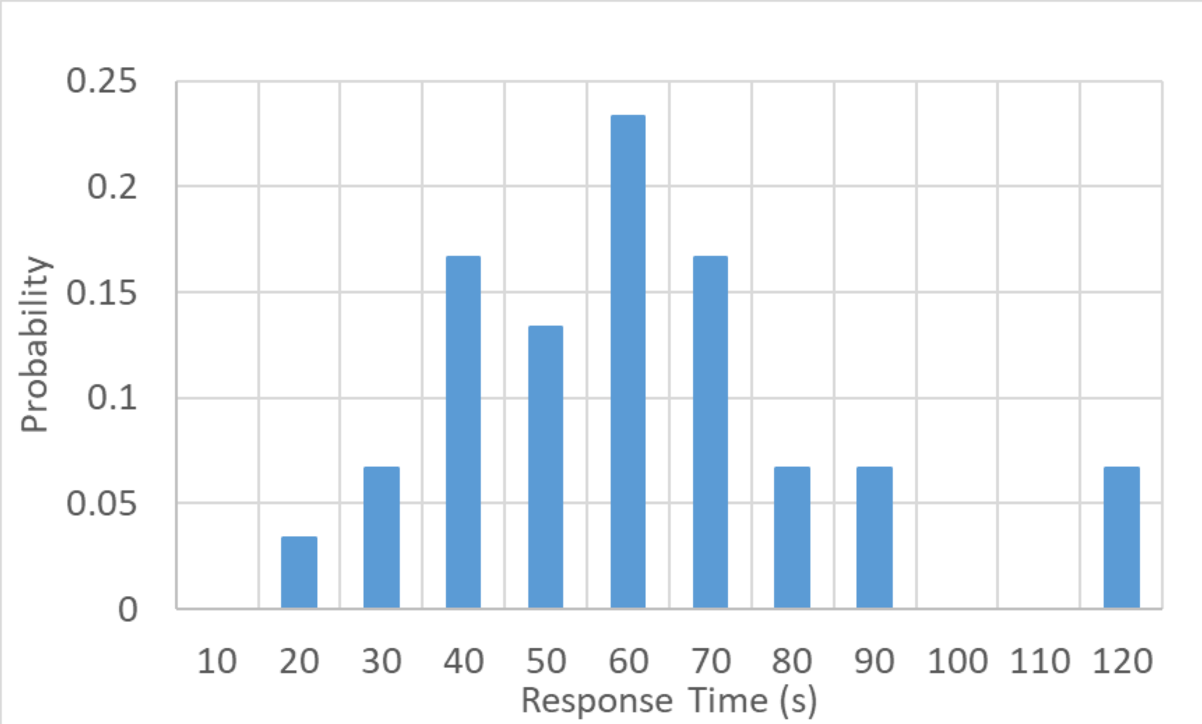


Figure 59. Overall response time distribution for Trial 2 (jumpform only).

4.2.2 Questionnaire data for Trial 2

The questionnaire was completed by 34 workers, with 28 of these questionnaires being completed in English and six completed in Romanian (all paper questionnaires). This represented a much higher percentage of the number of workers on site (74%), but 18 of the workers filling in the questionnaires stated that they were on the ground floor at the time of the alarm. This is unlikely to be correct as all 46 workers who evacuated were located above ground and so these replies cannot be relied upon. As in Trial 1 there was insufficient data collected from these questionnaires to conduct a meaningful statistical analysis and thus it was combined with that from other trials, the results of which are presented in Section 4.6.

4.2.3 Total evacuation time data for Trial 2

The first worker exited the building after 28 s and the last worker (46th worker) exited the building 9 m 14 s after the start of the alarm.

In total 46 workers were observed exiting the building: 43 of these exited the North Core via the externally located temporary scaffold dogleg stairs and three workers exited the South Core via externally located temporary scaffold dogleg stairs. Of the three workers exiting the South Core, one was already descending the external staircase when the alarm sounded and the other two were on Level 1 and near to the staircase. None of the occupants used the internally located staircase in the South Core and none of the occupants attempted to use either hoist.

Of the 43 workers from the North Core, the first worker exited after 34 s and the last worker exited after 9 m and 14 s. The 43 workers produced the exit curve presented in Figure 60. The average exit flow achieved by the 43 workers in this trial was 0.08 p/s. The low exit flow in Trial 2 was due to the majority of workers (30 of the 43) being located in the formworks, resulting in a few workers exiting early (those located low down in the main part of the building) while the majority exited later.

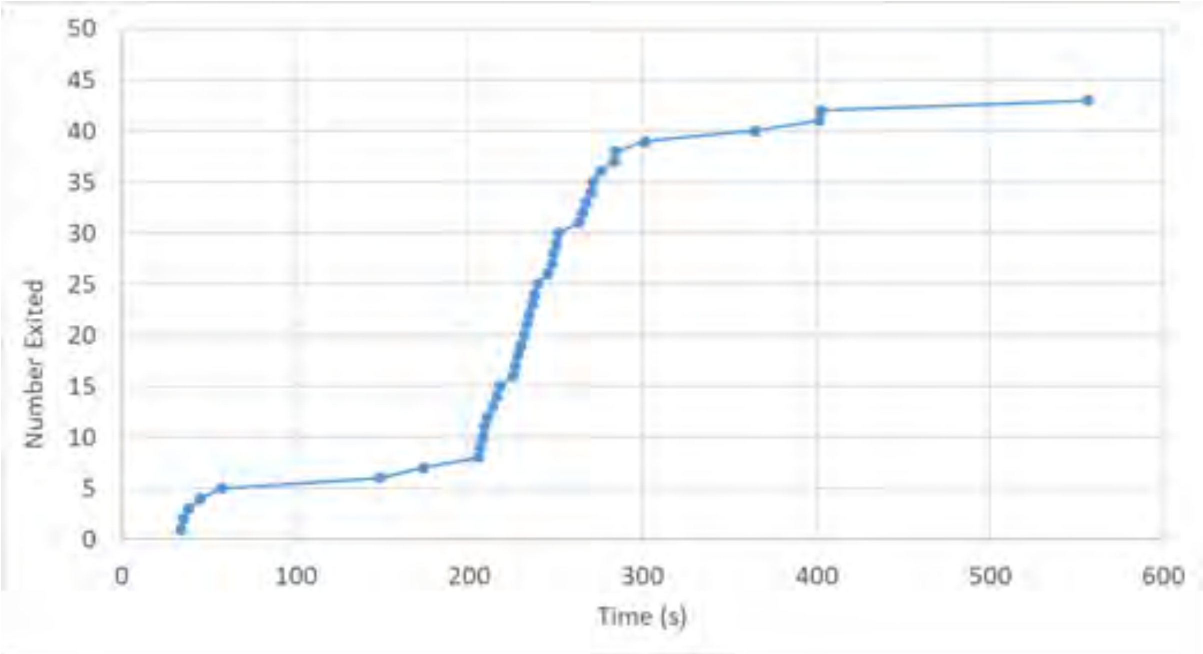


Figure 60. Overall exit curve for the 43 workers from the North Core in Trial 2.

Due to the simplicity of the construction site and the small number of workers present, this data-set would not make an appropriate validation data-set.

4.2.4 Stair usage data from Trial 2

For Trial 2 stair usage data was collected from the last flight of the temporary scaffold dogleg stair located at the exit point for the evacuation (see Figure 61). The flight consisted of nine treads from the half landing down to the base of the stair which had a hinged door at the exit point. The data was collected over a period from 09:00:35 to 09:09:20 after the alarm at 09:00:05. In total 44 people were observed to use the stair during this period with 32 spacing data points collected from 26 individual workers – one worker re-entered and so was observed descending twice. While there were a number of isolated workers who used the stair during the measurement period, workers also came down the stairs in groups, some in groups of two workers while others were in larger groups of four (see Table 11). As identified in Section 3.8, a group is defined as a continuous collection of people who when on the flight are separated by fewer than five treads.

Figure 61. Stairs in Trial 2 used to collect stair usage data.

Depicted in Figure 62 is a group of four workers descending the stairs. Analysis of the images suggests:

- Figure 62a:
  - there are 2 people on the flight plus 1 on the landing
  - first person is on tread 3, second person on tread 6
  - average spacing of 2 treads.
- Figure 62b, 1 s after the first image:
  - there are 3 people on the flight plus 1 on the landing
  - first person is on tread 1, second person is on tread 4, third person is on tread 9
  - spacing varies from 2 to 4; average spacing of 3 treads.
- Figure 62c, 1.5 s after the first image:
  - there are 2 people on the flight plus 1 on the landing and 1 has exited
  - first person is on tread 2, second person is on tread 7
  - average spacing of 4 treads.
- Figure 62d, 2 s after the first image:
  - there are 2 people on the flight plus 2 have exited
  - first person is on tread 5, second person is on tread 8
  - average spacing of 2 treads.
- Figure 62e, 3 s after the first image:
  - there are 2 people on the flight plus 2 have exited
  - first person is on tread 2, second person is on tread 6
  - average spacing of 3 treads.
- Figure 62f, 3.5 s after the first image:
  - there are 2 people on the flight plus 2 have exited
  - first person is on tread 1, second person is on tread 4
  - average spacing of 2 treads.

For this group, the maximum number of workers on the flight was 3, the spacing varied from 2 treads to 4 treads, with an average spacing of 3.0 treads and a mode spacing of 2 treads.

(a) First person of a group of four is on tread 3, with one other person on the stair and one more on the half landing.

(b) First person is on tread 1 with two others on the flight and one more on the half landing, 1 s after (a).

(c) One person has left the stair with two on the flight and one on the half landing, 1.5 s after (a).

(d) Two people have left the stair with two on the flight, 2 s after (a).

(e) Two people have left the stair with two on the flight, 3 s after (a).

(f) Two people have left the stair with two on the flight, 3.5 s after (a).

Figure 62. Group of four descending the temporary scaffold stairs in Trial 2.

Depicted in Figure 63 is a group of two workers descending the stairs. Analysis of the images suggests:

- Figure 63a:
    - there are 2 people on the flight
    - first person is on tread 5, second person is on tread 9
    - average spacing of 3 treads.
- Figure 63b, 0.5 s after the first image:
    - there are 2 people on the flight
    - first person is on tread 4, second person is on tread 8
    - average spacing of 3 treads.
- Figure 63c, 1 s after the first image:
    - there are 2 people on the flight
    - first person is on tread 1, second person is on tread 5
    - average spacing of 3 treads.

For this group of two workers, the maximum number of people on the flight was 2, the spacing was always 3 treads, with the average spacing of 3.0 treads.

(a) Start of a group of two on the final flight; the first person is on tread 3, with one other person on the stair and one more on the half.

(b) Group of two depicted 0.5 s after (a).

(c) Group of two depicted 1 s after (a).

Figure 63. Group of two descending the temporary scaffold stairs in Trial 2.

This type of analysis was undertaken for all the identified groups in the video sequences studied. A summary of the results are presented in Table 11 with the full results presented in Appendix 4. The spacing frequency is presented in Figure 64 while the frequency distribution for the number of people on the flight is presented in Figure 65.

Table 11. Summary of interpersonal spacing on stair flight for Trial 2.

Parameter	Data
Alarm time (hh:mm:ss)	09:00:05
Start time of analysis (hh:mm:ss)	09:00:35
End time of analysis (hh:mm:ss)	09:09:20
Number of groups observed	10
Minimum group size	2
Maximum group size	4
Mean group size	2.6
Number of individual workers observed	26
Number of individual spacing measurements	32
Minimum spacing observed	2
Maximum spacing observed	4
Mean spacing observed	2.9
Minimum number of workers on stair flight	1
Maximum number of workers on stair flight	3
Mean number of workers on stair flight	1.8

From Figure 64 it can be seen that modal stair spacing is 3 (14 occurrences representing 44% of the data), with the next most common stair spacing being 2 (10 occurrences representing 31% of the data). Presented in Figure 65 is a frequency distribution for the number of people on the flight. As can be seen, the modal number of people to occupy the flight is 2 (26 occurrences representing 67% of the data), with the maximum number observed on the flight being 3 (3 occurrences representing 8% of the data).

Unfortunately, there is only a small number of data points in this data-set so it is difficult to draw firm conclusions concerning stair behaviour. Furthermore, of the data collected, the majority are based on groups consisting of two people (60% of the groups). When considering groups of two, it is clear that the stair occupancy can never exceed 2. Furthermore, as there is no one behind the second person, they are free to assume any spacing they desire as they are not under pressure from anyone behind them to assume a closer spacing with the person ahead. It is thus difficult to establish what the ***minimum*** preferred spacing is likely to be in situations where there are a number of people attempting to occupy a flight simultaneously.

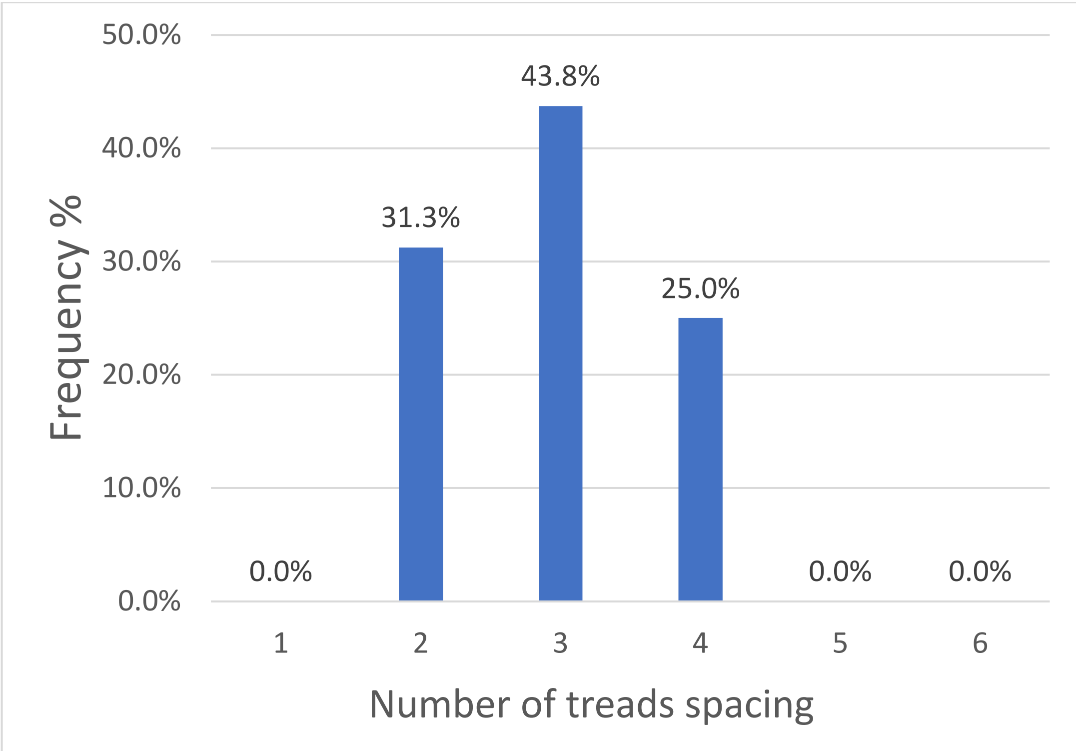


Figure 64. Occupant spacing on flight for Trial 2.

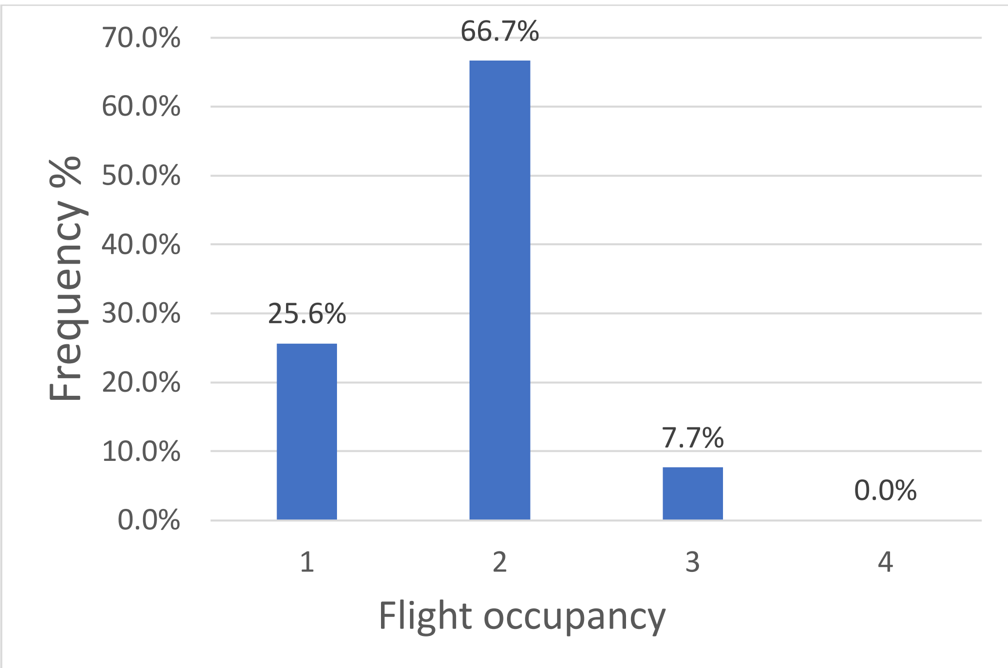


Figure 65. Flight occupancy for Trial 2.

Finding 2.4: A single flight of a single-lane temporary scaffold dogleg stair with nine treads per flight was monitored during the Trial 2 evacuation and it was noted that 44 people passed through the flight. The most frequent spacing between the occupants on the flight was 3 treads with a mean spacing of 2.9 treads and the maximum number of people that was accommodated on the flight was 3. The observed spacing is significantly different to that found on regular building stairs which is typically 1 tread between occupants. The lower interpersonal spacing on the temporary stair will have a negative impact on the flow capability of the stair, essentially decreasing the flow compared to a permanent stair of similar width. However, it is noted that the number of data points is small and the majority of these were associated with groups consisting of only two people.

4.3 Trial 3: Results from the full-scale evacuation

In this section results from the third full-scale evacuation trial conducted in 100 BG on 4 October 2017 are presented and discussed. At the time of the evacuation, the building consisted of 38 core levels and 33 completed or partially completed floors. In total there were 308 workers on site at the time of the evacuation. Detailed quantitative analysis of the nature of the RT distributions derived from these trials including a comparative analysis of the data derived from all four trials and any possible generalisations derived from the combined data is presented in Section 4.6. In this section we focus on exploring the nature of the data generated from this trial and identifying factors which may have influenced the data.

4.3.1 Response times extracted from Trial 3

From the video footage captured during Trial 3, 308 workers were recorded exiting the building. From these workers, 53 response times were extracted from the video footage, representing just 17% of the workforce present at the time of the trial. The building had reached its final height prior to this trial and, as a result, the slipformwhich had been present during Trial 1 had been dismantled and removed.

The works being undertaken during this trial consisted of MEP, laying decking, installing rebar and installing glazing, and involved workers working at height and also workers supervising crane activities. The response times for these different groups are summarised in Table 12. Much of the work undertaken within the building was on completed floors and consisted primarily of MEP activities (22 MEP workers). The MEP work captured on video footage (between Levels 6 and 23) included the installation of pipework, electric cables and air conditioning units, and produced an average response time of 88.5 s (see Table 12).

Glazing was being installed by two workers on Level 10. At the time of the alarm these workers were preparing to install a glass pane and thus were not undertaking any works that needed to be made safe, i.e. there was not a pane of glass suspended over the edge of the building. As a result, these workers were able to respond more rapidly than the glaziers observed in Trial 1, with an average response time of 75 s (see Table 12) – which is 61% of the mean response time of the glaziers in Trial 1 (195 s).

On the upper floors, decking and rebar were being laid, with the rebar workers requiring an average of 21.0 s to respond and the decking workers requiring an average of 54.7 s to respond (see Table 12). The RT distribution for Trial 3 is presented in Figure 67. As can be seen, the RT distribution is lognormal in appearance with minimum, maximum and mean response times of 0.9 s, 191.2 s and 61.6 s respectively.

Finding 3.1: The response time distribution for the high-rise construction site observed in Trial 3, excluding the formworks, appears to follow the usual lognormal distribution, with minimum response time of 0.9 s, a maximum response time of 191.2 s and a mean response time of 61.6 s.

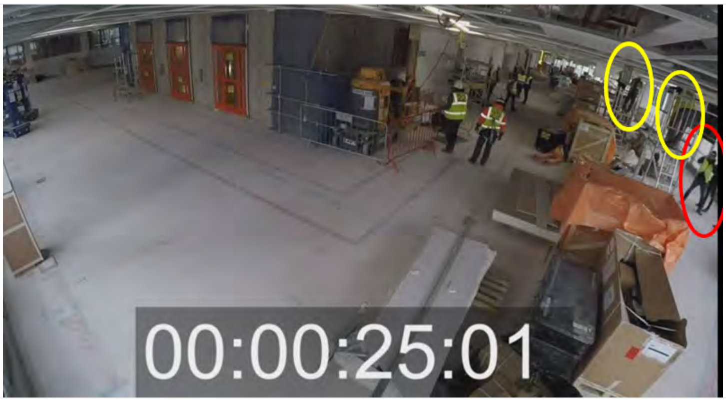
Table 12. Summary of response time distributions split into common tasks for Trial 3.

	Minimum Response Time (s)	Mean Response Time (s)	Maximum Response Time (s)	Standard Deviation	Number of Workers	Number of Supervisor Interventions
Overall	0.9	61.6	191.2	47.1	53	9
Installing Rebar	8.4	21.0	35.4	7.4	12	5
Crane Supervisors	0.9	44.7	103.2	39.3	7	0
MEP	20.4	88.5	191.2	46.9	20	2
Installing Decking	16.1	54.7	123.1	41.0	8	0
Glaziers	14.3	21.9	35.4	7.7	5	0
Working At Height	42.0	103.9	141.5	44.1	3	2

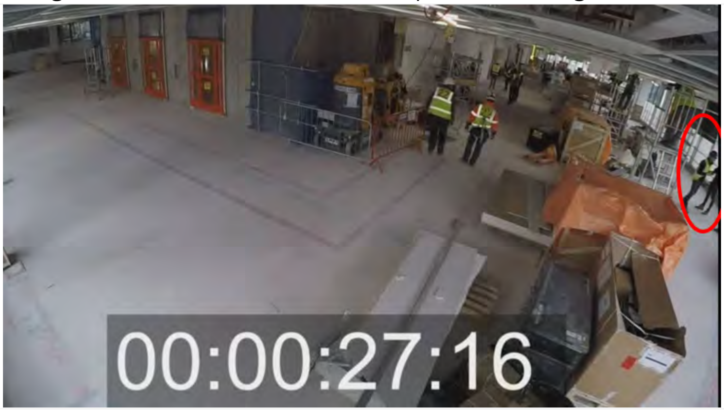
As in Trial 1, the supervisors in Trial 3 played a significant role in reducing the response time of workers. This is demonstrated in Figure 66 where a supervisor intervention with a team of four MEP workers encourages the workers to start their evacuation time, decreasing their likely response times. When the alarm sounded, all four workers disengaged from their pre-alarm activities, and looked to the supervisor for confirmation. Some 15 s after the sounding of the alarm, the supervisor initiates a call on his mobile phone, presumably calling someone in authority for confirmation as to the nature of the alarm (see Figure 66a). The call is ended some 26 s after the start of the alarm and the supervisor is seen giving instructions to the workers (see Figure 66b). Some 36 s after the start of the alarm, all four workers start to evacuate (see Figure 66c) and within 73 s of the start of the alarm, the area is clear of workers. All four workers responded very rapidly to the instructions of the supervisor. This demonstrates how effective supervisors can be in reinforcing the alarm cues and motivating workers to start their evacuation.

Finding 3.2: In Trial 3, as in Trial 1, supervisors play an important role in reducing the response time of workers. Without the intervention of supervisors, workers may delay disengaging from pre-alarm activities and/or waste time in performing information tasks as they seek to confirm the nature of the incident.

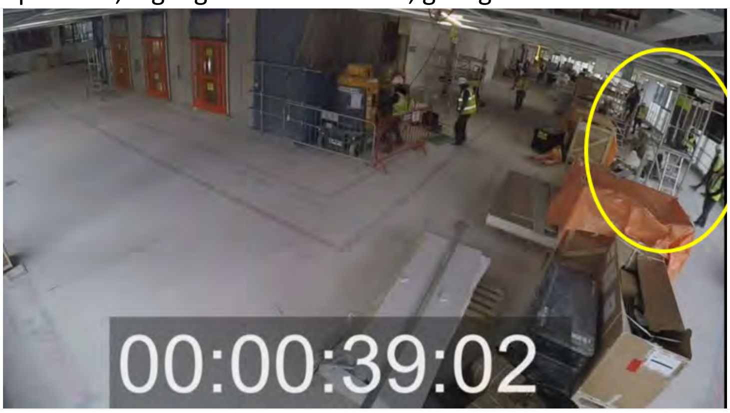
The RT distribution for the building (excluding formworks) in Trial 3 closely resembles that for Trial 1 (see Figure 14), not only in general appearance but also in the range of response times produced, with both distributions having similar minimum and maximum response times: 8.8 s and 203.8 s respectively for Trial 1 with 0.9 s and 191.2 s respectively for Trial 3. The mean response times are also similar: for the building (excluding formworks) in Trial 1 was 78.5 s while in Trial 3 it was 61.6 s. This similarity is somewhat surprising given that the building in Trial 1 only had 19 core levels completed with 12 floors under construction while in Trial 3 all 38 floors were in various stages of completion. Thus the building in Trial 3 was twice the height of the building in Trial 1, yet the RT distribution is similar. This surprising finding suggests that response times on construction sites may not be severely impacted by the height of construction.



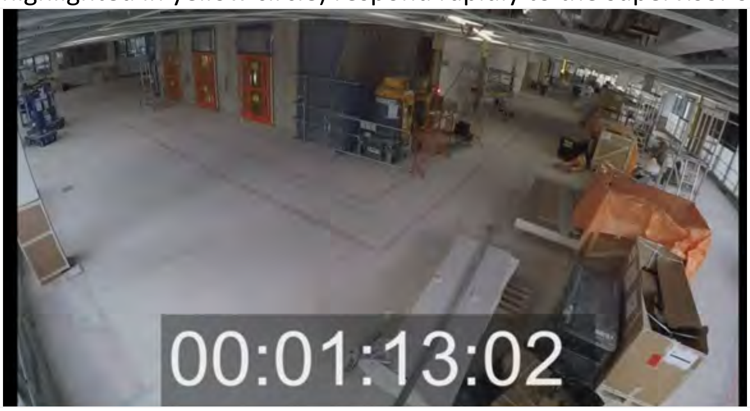
(a) Supervisor (highlighted in the red circle) is on his telephone. Two workers working at height await confirmation from supervisor. Two other workers standing beside the supervisor (whose feet/legs can be seen in the red circle) also awaiting confirmation.



(b) Supervisor, highlighted in red circle, giving instructions to workers.



(c) Workers (highlighted in yellow circle) respond rapidly to the supervisor's instructions.



(d) Area clear 73 s after alarm.

Figure 66. Impact of supervisor on worker response times in Trial 3.

Finding 3.3: Trials 1 and 3 not only have similar shaped distributions but also similar maximum, minimum and mean response times, even though in Trial 1 the building only extended to 19 core levels while in Trial 3 the building had 38 core levels. This suggests that the height of construction may not have a significant impact on worker response times.

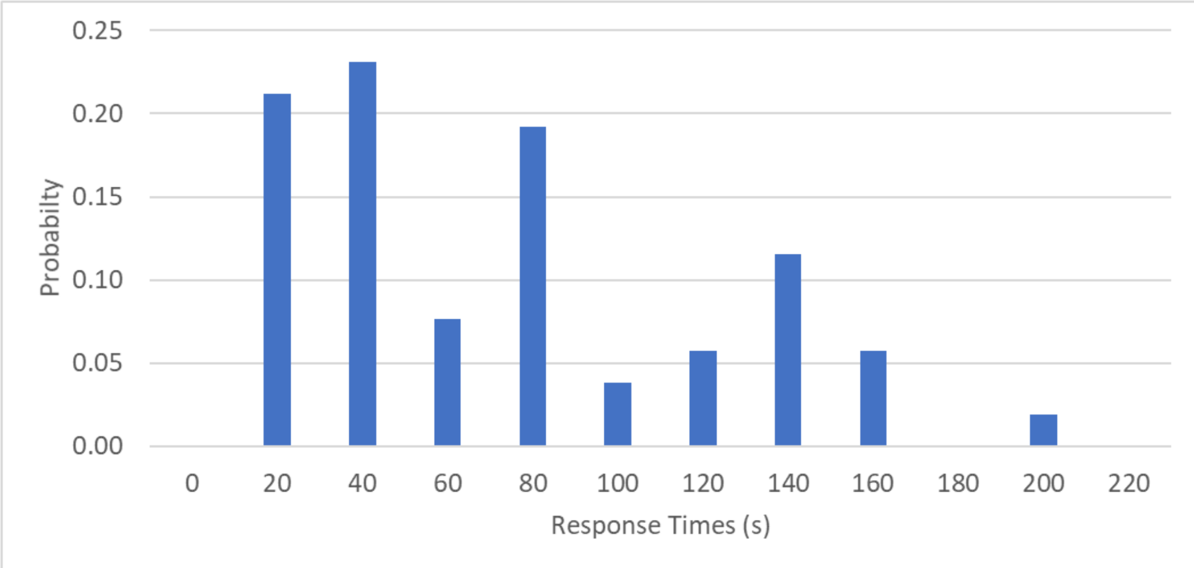


Figure 67. Overall response time distribution for Trial 3.

4.3.2 Questionnaire data for Trial 3

The questionnaire was completed by 15 workers. However, these questionnaires were returned partially completed.

4.3.3 Total evacuation time data for Trial 3

The first worker exited the building after 20 s and the last worker exited the building 18 min 18 sec after the start of the alarm. The average exit flow achieved by the 308 workers is 0.29 p/s. The exit curve for Trial 3 is depicted in Figure 68. As described earlier, there were four exit points from the building, three via the stairs and one via the welfare entrance/exit on the 1st floor. Of the 308 workers observed exiting the building, 212 workers (69%) exited via the exit on the 1st floor through the welfare entrance/exit.

As in Trial 1, unfortunately there were not sufficient cameras to monitor the entire construction site. As a result, it is not possible to determine the starting location of all 308 workers or even to establish the starting floors. Without reliable information relating to the starting location of each worker it will not be possible to establish a validation data-set from this trial.

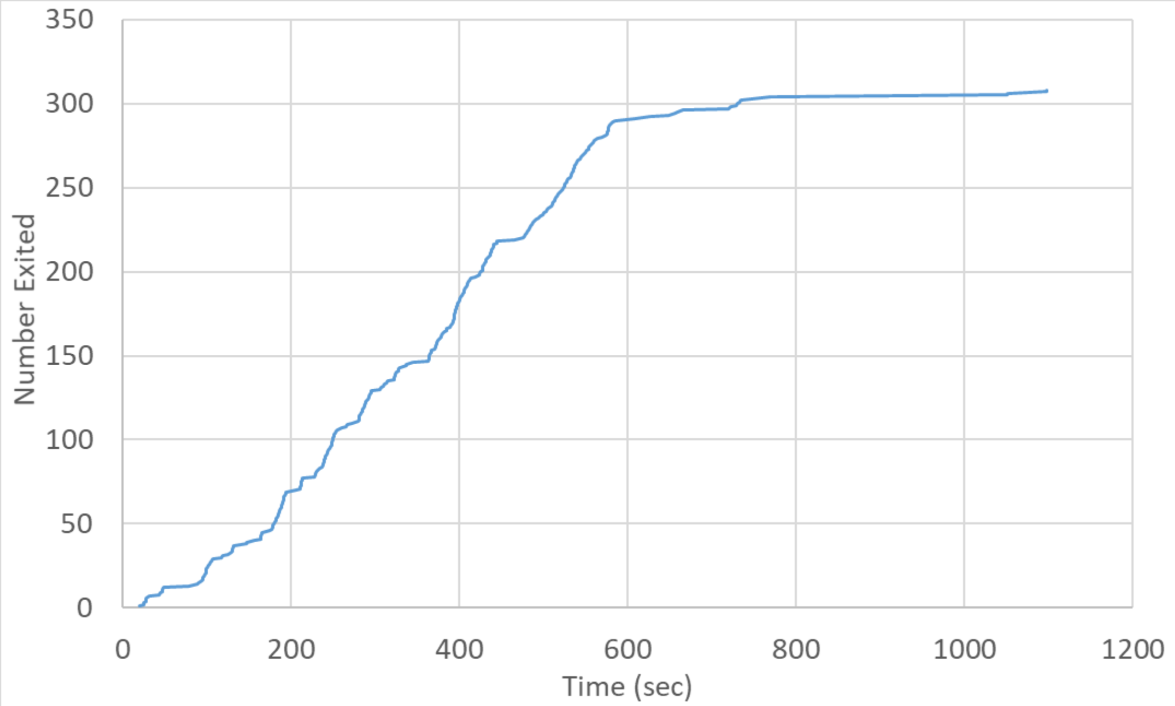


Figure 68. Overall exit graph for Trial 3.

4.3.4 Stair usage data from Trial 3

No stair usage data was extracted from Trial 3.

4.4 Trial 4: Results from the full-scale evacuation

In this section results from the last full-scale evacuation trial conducted in 22 BG on 16 November 2017 are presented and discussed. At the time of the evacuation, the North Core of the building consisted of 32 core levels with 20 levels in various stages of completion and three decks in the jumpform located at Level 33 (note, only the North Core was monitored in this trial). In total there were 388 workers who evacuated from the building. Detailed quantitative analysis of the nature of the RT distributions derived from these trials including a comparative analysis of the data derived from all four trials and any possible generalisations derived from the combined data is presented in Section 4.6. In this section we focus on exploring the nature of the data generated from this trial and identifying factors which may have influenced the data.

4.4.1 Response times extracted from Trial 4

From the video footage of the trial, 388 workers were recorded as exiting the building. A total of 82 response times were extracted from the video footage, of which 38 (46%) response times were for workers in the jumpform. The overall RT distribution for the entire building is depicted in Figure 69. As in Trial 1 the distribution appears to follow the usual lognormal appearance.

It is noted that in Trial 4, at the time of the alarm, 102 staff were located on Level 3. These staff were located in site management offices, the staff canteen and changing rooms. No effort was made to capture their response times.

The first worker responded to the alarm 4.8 s after the alarm sounded; they were located in the jumpform and were involved in installing rebar in preparation for a concrete pour. The last worker to respond to the alarm was a worker installing metal decking on Level 22 who started to evacuate 340 s after the start of the alarm.

Finding 4.1: Overall, the response time distribution for the high-rise construction site observed in Trial 4 appears to follow a lognormal curve, with minimum response time of 4.8 s and maximum response time of 340.2 s.

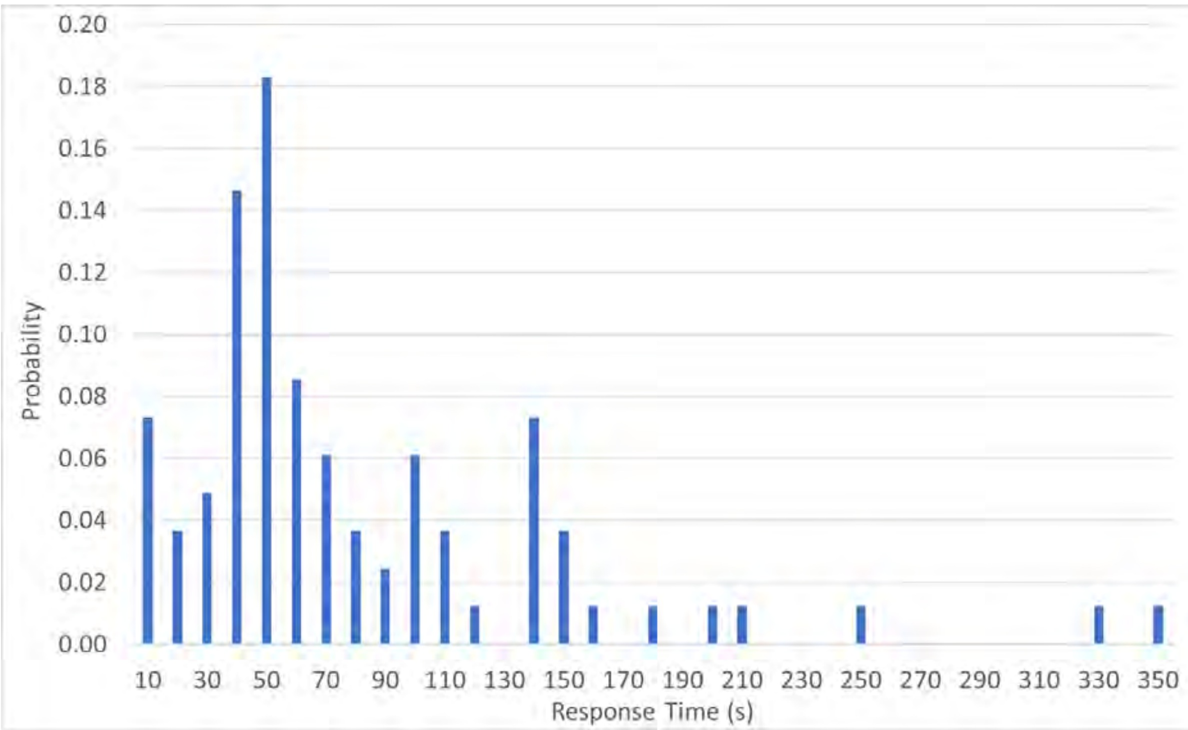


Figure 69. Overall response time distribution for Trial 4.

Excluding those in the jumpform, the response times for the main building vary from 9.0 s to 340.2 s with a mean of 75.3 s and a standard deviation of 73.1 s. As observed in Trial 1, the overall RT distribution can be divided into groups based upon common tasks being carried out by the workers. Table 13 presents a list of six common tasks along with the number of workers performing those tasks and a description of the RT distribution generated by each group of workers. Included in Table 13 are a group of workers who were not engaged in any specific tasks at the time of the alarm, but were observed to be walking – possibly to or from their work activity. Excluding those in the jumpform, the mean response time varies from 42 s for glaziers to 331 s for workers who were installing decking, with crane supervisors having a mean response time of 126 s, those installing MEP having a mean response time of 75 s, and those working at height having a mean response time of 56 s. The walking group have a mean response time of 47 s.

Finding 4.2: As observed in Trial 1, the nature of the pre-alarm activity that the worker was involved in (i.e. the nature of the work associated with worker group) will impact how rapidly they respond to the alarm, with glaziers responding on average the quickest (42 s) and workers installing metal decking taking the longest to respond (331 s). It is also noted that crane supervisors can also take a long time to respond to the alarm (126 s).

Table 13. Summary of response time distributions split into common tasks for Trial 4.

Task	Minimum Response Time (s)	Maximum Response Time (s)	Mean Response Time (s)	Standard Deviation	Number of Workers	Number of Supervisor Interventions
Overall	4.8	340.2	75.3	64.0	82	12
Walking	9.0	131.6	47.5	43.0	5	0
Installing Decking	322.2	340.2	331.2	9.0	2	1
Installing MEP	16.1	202.7	59.3	57.1	17	2
Glaziers	30.4	46.9	41.9	5.9	5	0
Crane Supervisors	81.6	149.8	125.9	24.6	5	0
Working at Height	32.5	108.9	56.5	24.1	10	4
Jumpform	4.8	247.7	75.4	51.6	38	5

As already noted in Trial 3, unlike the glaziers in Trial 1, the glaziers can have a relatively short average response time (42 s) compared to the other groups of workers (average of 75 s). The average response time for the glaziers in Trial 4 is comparable to those in Trial 3 (35 s), which is in stark contrast to those in Trial 1 (who responded on average after 195 s). As has been previously mentioned, this difference in response time is due to the type of task the worker was undertaking at the time of the alarm. Unlike the glaziers in Trial 1, at the time of the alarm the glaziers in Trial 3 and Trial 4 were not undertaking critical tasks that needed to be made safe. Thus it was possible for the glaziers in Trials 3 and 4 to abandon their tasks and start to evacuate relatively early.

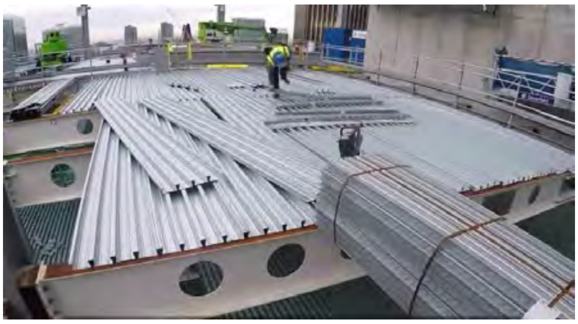
Finding 4.3: The nature of the work that glaziers are involved with enables them to have either short or long response times. However, if glaziers are on site it is possible that they will be involved in the type of activities that cannot be abandoned without making safe and so it is reasonable to adopt the longer response times for this group of workers to characterise their response, especially when making life safety assessments.

The walking group consisted of five workers that were not directly associated with any specific task as they were observed walking to or from their normal work activity at the time of the alarm. From Table 13 this group had a wide range of response times, varying from 9.0 s to 132.6 s. One of these workers was on his own, and on hearing the alarm he almost immediately started to evacuate (response time 9.0 s). Three other workers were in a loose group of workers who responded quite quickly to the alarm: 29.4 s, 32.2 s and 35.5 s. The fifth worker was also on his own at the time of the alarm but was engaged in a phone conversation. This worker continued with his phone conversation and only started his evacuation on completing his phone conversation, 131.6 s after the sounding of the alarm.

As in Trial 1, there were several isolated workers who generate long response times. Being isolated and not receiving the additional cues of seeing other workers respond to the alarm can result in very long response times. These difficulties can be compounded if the worker is wearing ear protectors.

Consider as an example an isolated worker located on floor 22 laying decking, captured by camera15. As the fire alarm sounds, the worker starts a short break. While the fire alarm is clearly audible (can be clearly heard on the video) the worker has ear protectors on and so cannot hear the alarm, and as there is no one else around does not receive any other cues (see Figure 70a). After 2 min 55 sec, the worker resumes work, still unaware of the alarm (see Figure 70b). He continues his work activities until he receives a mobile phone call. It is assumed that his phone is on vibrate. After 5 min 02 sec he reaches for his phone and is about to remove his ear protectors (see Figure 70c). Having removed his ear protectors, the worker answers the phone while the alarm is sounding and engages in a conversation. It is not until 5 min 23 sec that the worker begins his evacuation movement phase, while still on the phone (see Figure 70d). At 5 min 32 sec a supervisor arrives while the worker is moving away. Had it not been for the phone call, this worker would have continued with his pre-alarm activity until the supervisor had arrived and engaged the worker.

(a) Isolated worker laying decking on floor 22 at the sounding of the alarm.



(b) After 175 s the worker resumes work, still unaware of the alarm.

(c) At 302 s, the worker receives a mobile phone call and reaches for his phone.

(d) Worker begins his evacuation movement phase 323 s after the sounding of the alarm.

Figure 70. Isolated worker delaying his response to the alarm and only disengaging when he removes his ear protectors to answer the phone.

Unlike in Trial 1, there were only 12 supervisory interventions required to encourage workers to respond to the alarm. Ignoring the supervisory interventions in the formworks, in Trial 4 only 16% of the recorded response times (seven out of 44) involved a supervisor intervention while in Trial 1 58% involved supervisor intervention (35 out of 60).

Furthermore, the seven workers who responded after the alarm and after a supervisor intervention had a mean response time of 47.1 s, while the 44 workers who responded without needing a staff intervention did so on average after 79.7 s. So workers who received two stimuli – alarm and supervisor intervention – tended to react 41% quicker than those who only received a single stimuli – the alarm. So without the staff intervention, it is reasonable to assume that the response time of those who received the intervention would have been at least as long as those who responded only to the alarm and perhaps, depending on the circumstances (e.g. isolated workers), significantly longer.

Finding 4.4: According to the data generated from Trial 4, only 16% of workers (excluding those in the formworks) required some form of supervisor intervention to encourage them to disengage from their pre-alarm activities and start engaging in evacuation activities. Without these interventions, the response times of the workers are likely to have been much longer. This highlights the importance of supervisors in reducing the response times of workers on construction sites. However, it is noted that this is significantly less than that observed in Trial 1 where 58% of the workers required a supervisor intervention.

As in Trial 1 and Trial 3, we can separate the response times for the formworks workers from those of the rest of the building and produce two separate RT distributions. The RT distribution for the entire building excluding the jumpform (44 workers) is depicted in in Figure 71, while the RT distribution for the jumpform workers (38 workers) is depicted in Figure 72. The RT distribution for the building excluding the jumpform clearly resembles a lognormal distribution while the distribution for the jumpform could be argued to be more normal in appearance than lognormal. The response time in the jumpform has a minimum, maximum and average response time of 9.0 s, 340.2 s and 75.3 s respectively.

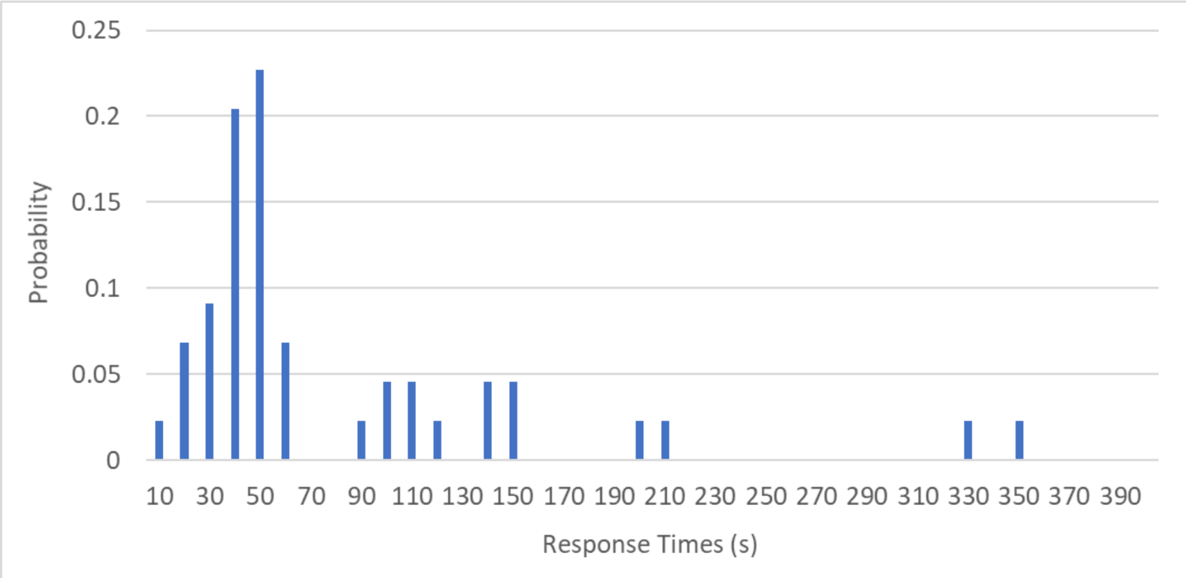


Figure 71. Response times for workers in Trial 4 excluding the jumpform.

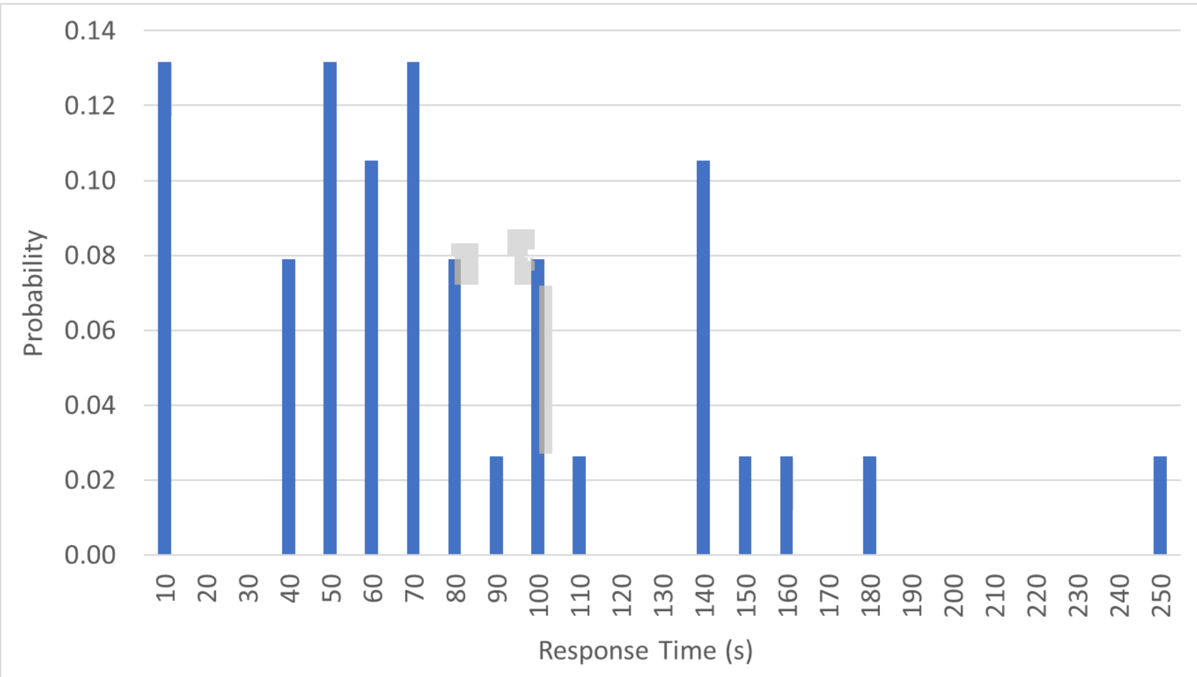


Figure 72. Response times for workers in the jumpform during Trial 4.

At the time of the alarm the work being undertaken in the jumpform was the installation of steel rebar in preparation for a concrete pour, as in Trial 2. This is very different to the work being done during Trial 1, which involved dismantling the slipform. Furthermore, in Trial 4, six supervisors were present at the time of the alarm. And unlike in Trial 2, their procedure involved not only alerting the workers of the need to evacuate, but they were also required to stay behind to ensure that the jumpform was clear of workers before they self-evacuated. This could explain the usually long response times observed in the jumpform. Presented in Figure 73 is the modified RT distribution for the jumpform; removing the six supervisors from the distribution has reduced the maximum response time from 247.7 s to 133.2 s and the mean response time from 75.4 s to 58.4 s. As a result, the maximum and mean response time for the jumpform workers in Trial 4 is now more similar to that in Trial 2 (114.7 s and 55.6 s). Furthermore, the distribution now more closely resembles a normal distribution.

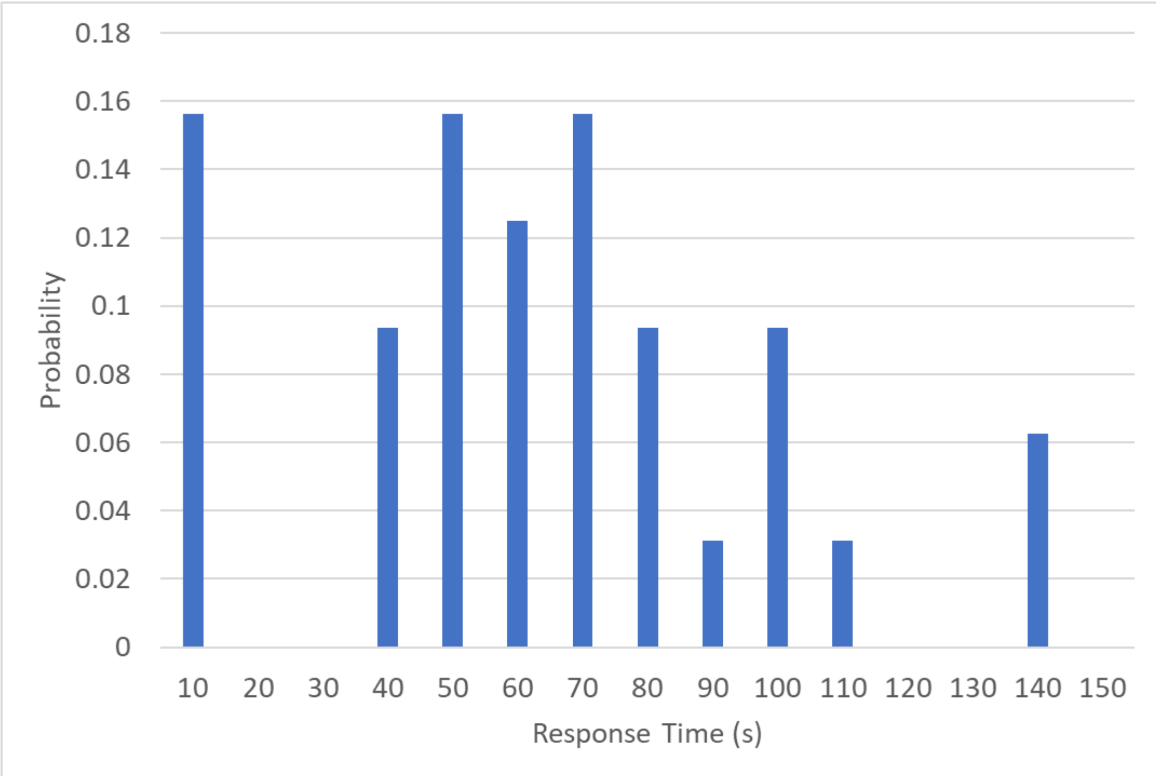


Figure 73. Response time distribution for workers in jumpform for Trial 4 excluding the six supervisors.

Finding 4.5: The response time distribution for Trial 4 workers located in the formworks appears to be defined by a normal distribution with a minimum of 4.8 s, a maximum of 133.2 s and a mean response time of 58.4 s, excluding the response times of six supervisors. As in Trial 2, it is noted that the work undertaken in the formworks at the time of the alarm was critical which may have impacted the response behaviour of the workers.

The difference in response time distributions for the formworks and the rest of the building observed in all four trials supports the view that the response time distribution for high-rise construction sites cannot easily be described by a single distribution, but may require two distributions to describe the response behaviour of the two distinct populations.

Finding 4.6: While the response times for the workers in the formworks in Trial 4 and Trial 2 (mean response time 58 s and 56 s respectively) are (90%) longer than those in Trial 1 (29 s), this can be explained by the time-critical nature of the work being undertaken within the formworks in Trials 4

and 2 (installing rebar ahead of a concrete pour) compared to Trial 1 (dismantling the formwork). This supports the view that the nature of the work that the worker is engaged in at the time of the alarm will determine the speed of their response.

Finding 4.7: The response time distribution for the workers in the formworks in Trial 1 and Trial 2/4 may define either extreme of response time distributions for this region of the building, with Trial 1 representing the 'fast end' and Trial 2/4 representing the 'slower end'. Given the nature of the work conducted in the frameworks, both types of activity are unlikely to occur at the same time. However, it should be noted that work associated with concrete pours is likely to result in even longer response times than those for Trial 2/4.

4.4.2 Questionnaire data for Trial 4

No completed questionnaires were returned. Several questionnaires were returned but with only partial replies.

4.4.3 Total evacuation time data for Trial 4

From the video footage captured during Trial 4, 388 workers were recorded as exiting the building. This figure excludes the last two people to exit the building who were two supervisors undertaking a sweep of the entire building from ground floor to top and back down again.

The first worker was recorded as exiting the building 21 s after the alarm was sounded. The time for the final worker to exit the building (excluding the two supervisors) is 1,247 s (20 min 47 sec). The exit curve for the 388 workers is presented in Figure 74. The average exit flow achieved by these 388 workers is 0.32 p/s. The long tail in the distribution represents workers who on exiting down to the third level decided to go to the welfare area to possibly change or collect belongings thus prolonging their evacuation times. In addition, the tail is also impacted by workers who were already in the welfare area on the third level, possibly in the canteen or changing facilities.

Finally, the specific description of the building layout is described in Section 5.1.1.

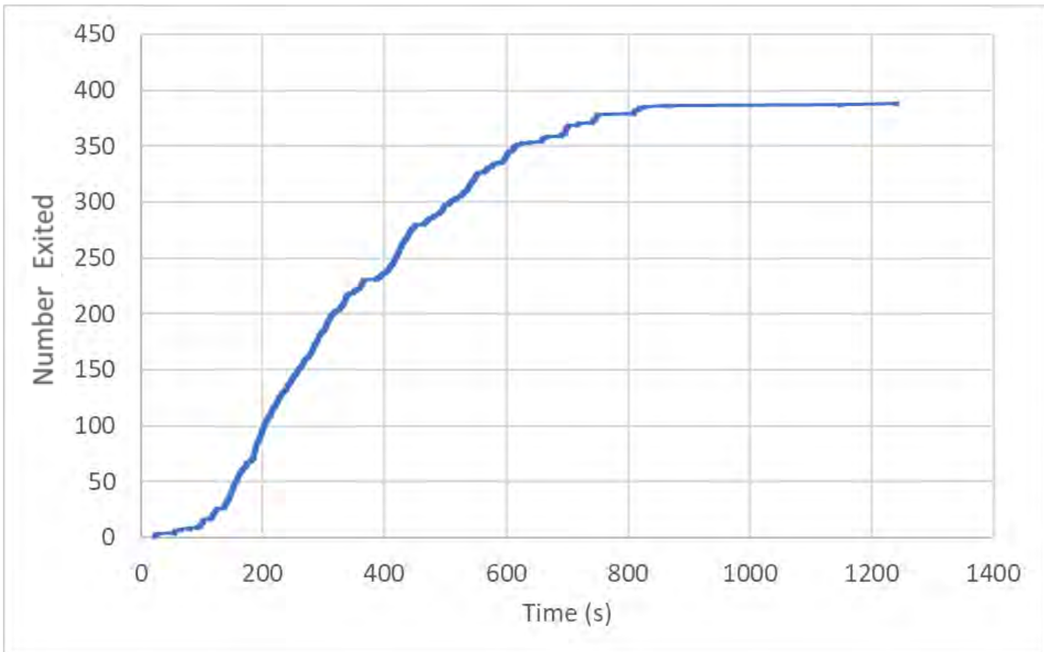


Figure 74. Overall exit graph for Trial 4 with the last two workers (supervisors) removed.

4.4.4 Stair usage data from Trial 4

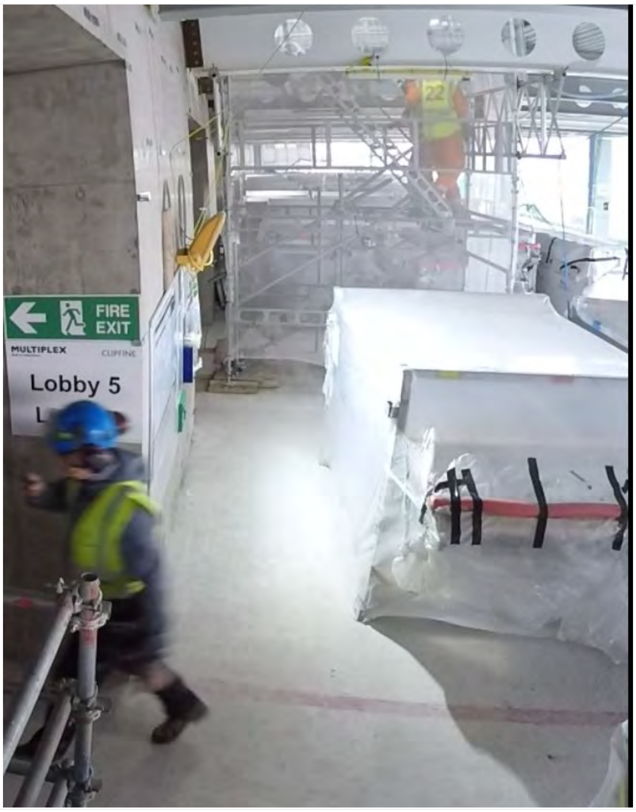
For Trial 4 stair usage data was collected from the last flight of the temporary scaffold dogleg stair located on Level 8 (see Figure 75). The flight consisted of nine treads from the half landing down to the base of the stair and is the same flight as that measured in Trial 2 (see Section 4.2.4). The data was collected over a period from 09:31:56 to 09:48:56 after the alarm at 09:30:59. In total 135 workers were observed to use the stair during this period with 192 spacing data points collected from 104 individual workers. While there were a number of isolated workers who used the stair during the measurement period, workers also came down the stairs in groups, some in groups of two workers while others were in larger groups of up to eight (see Table 14). As identified in Section 3.8, a group is defined as a continuous collection of people who when on the flight are separated by fewer than five treads.

Figure 75. Stairs in Trial 4 used to collect stair usage data showing tread numbering.

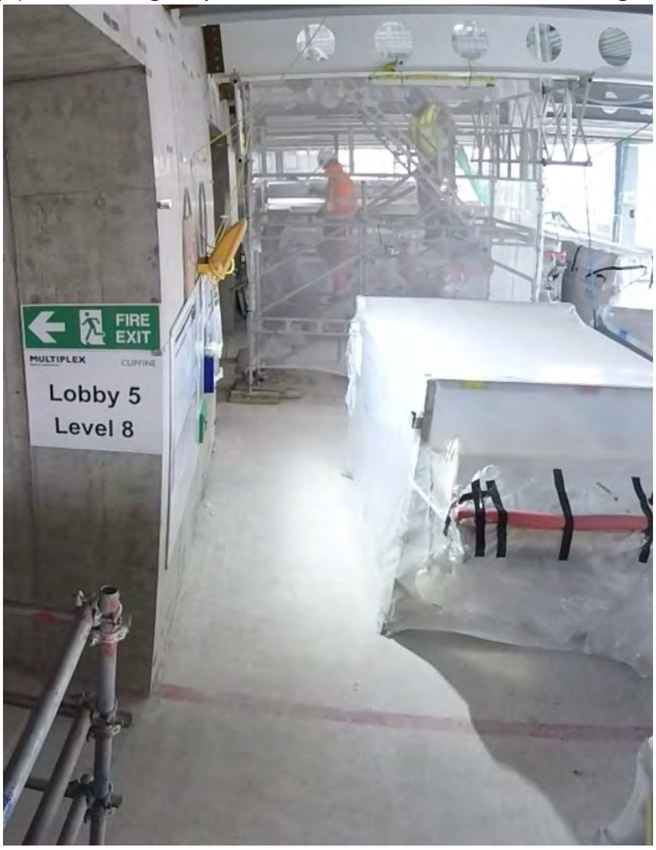
Depicted in Figure 76 is a group of two workers descending the stairs. Analysis of the images suggests:

- Figure 76a:
  - there are 2 people on the landing.
- Figure 76b, 1 s after the first image:
  - there are 2 people on the flight
  - first person is on tread 5, second person is on tread 9
  - average spacing of 3 treads.
- Figure 76c, 2 s after the first image:
  - there are 2 people on the flight
  - first person is on tread 1, second person is on tread 5
  - average spacing of 3 treads.

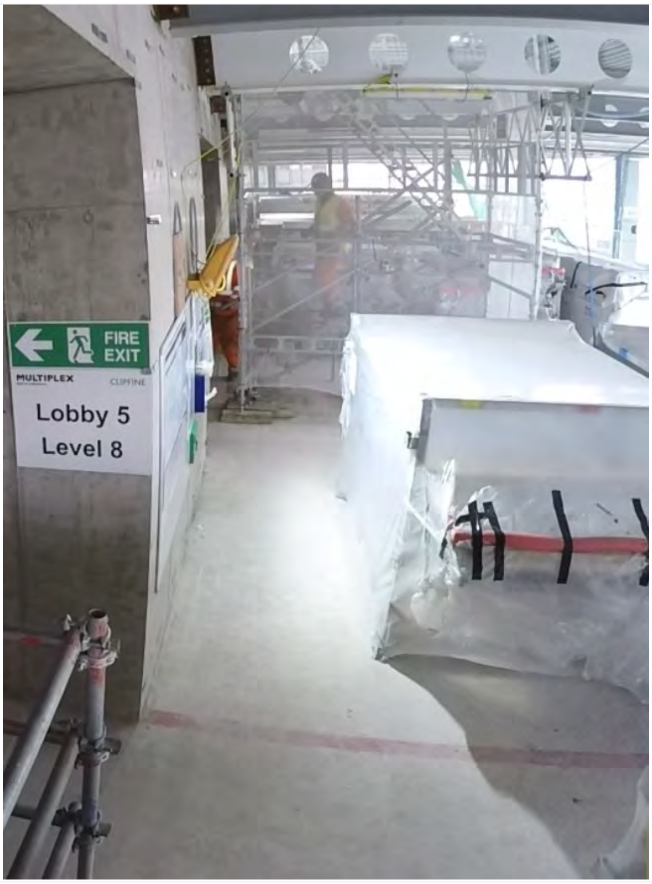
For this group of two workers, the maximum number of people on the flight was 2, the spacing was always 3 treads, with the average spacing of 3.0 treads.



(a) Start of a group of two about to enter the final flight.



(b) Group of two depicted 1 s after (a).



(c) Group of two depicted 2 s after (b).

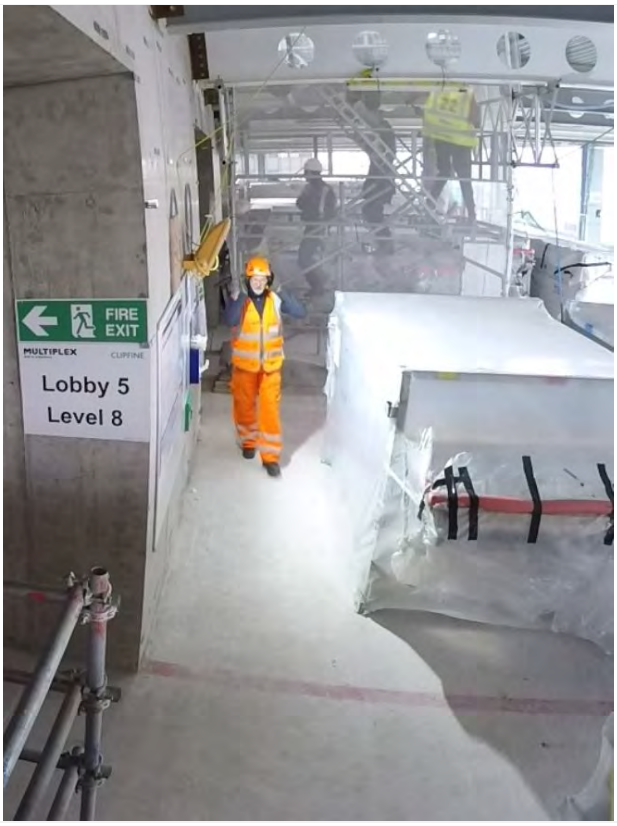
Figure 76. Group of two descending the temporary scaffold stairs in Trial 4.

Depicted in Figure 77 is a group of six workers descending the stairs. Analysis of the images suggests:

- Figure 77a:
    - there are 3 people on the flight plus 1 on the landing
    - first person is on tread 2, second person on tread 5 and third person on tread 8
    - average spacing of 2 treads.
- Figure 77b, 1 s after the first image:
    - there are 3 people on the flight plus 1 on the landing and 1 has exited
    - first person is on tread 2, second person is on tread 6, third person is on tread 9
    - average spacing of 3 treads.
- Figure 77c, 2 s after the first image:
    - there are 3 people on the flight plus 2 on the landing and 1 has exited
    - first person is on tread 1, second person is on tread 5, third person is on tread 7
    - spacing varies from 3 to 1 with average spacing of 2 treads.
- Figure 77d, 3 s after the first image:
    - there are 3 people on the flight plus 1 on the landing and 2 have exited
    - first person is on tread 3, second person is on tread 5, third person is on tread 8
    - spacing varies from 2 to 1 with average spacing of 1.5 treads.
- Figure 77e, 4 s after the first image:
    - there are 2 people on the flight plus 1 on the landing and 3 have exited
    - first person is on tread 3, second person is on tread 7
    - average spacing of 2 treads.
- Figure 77f, 5 s after the first image:
    - there are 2 people on the flight plus 4 have exited
    - first person is on tread 5, second person is on tread 8

- average spacing of 2 treads.
- Figure 77g, 6 s after the first image:
  - there are 2 people on the flight plus 4 have exited
  - first person is on tread 3, second person is on tread 6
  - average spacing of 2 treads.
- Figure 77h, 7 s after the first image:
  - there are 2 people on the flight plus 4 have exited
  - first person is on tread 1, second person is on tread 4
  - average spacing of 2 treads.

For this group, the maximum number of people on the flight was 3, and the spacing varied from 1 tread to 3 treads, with an average spacing of 2.1 treads.

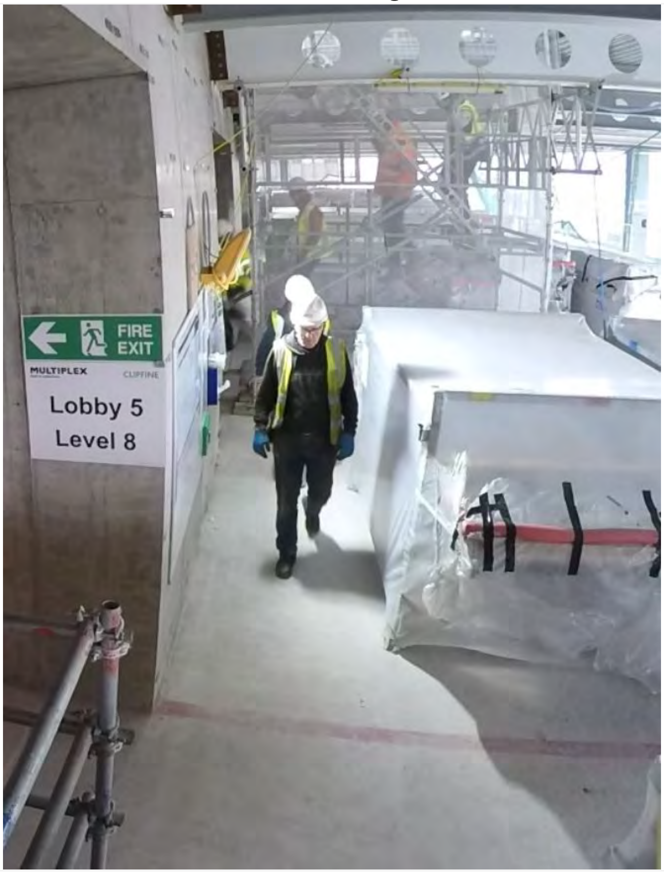


(a) First person of a group of six is on tread 2, with two other people on the stair and one more on the half landing.

(b) First person has left the stair with three on the flight and one more on the half landing, 1 s after (a).

(c) First person has left the stair with three on the flight and two on the half landing, 1 s after (b).

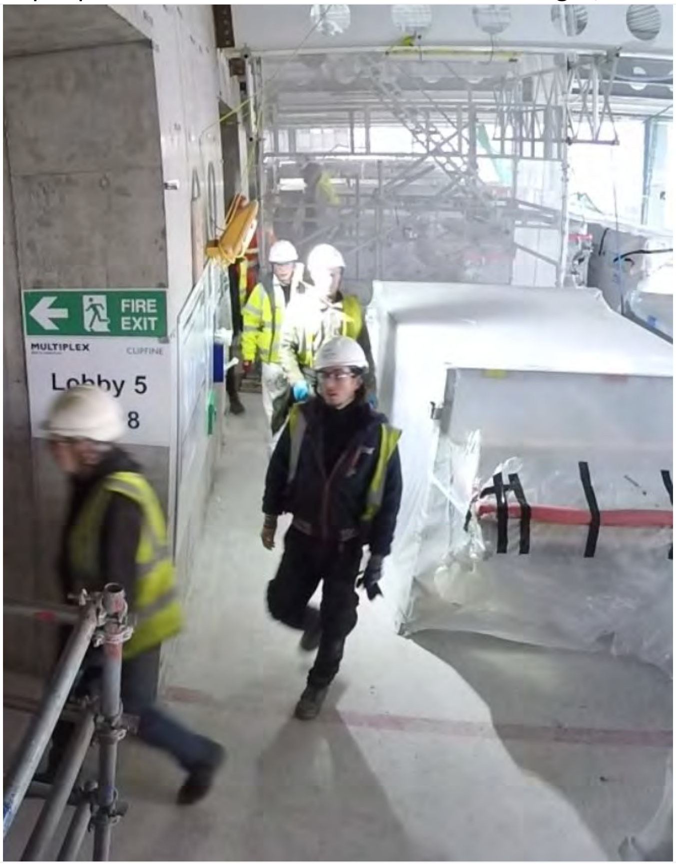
(d) Two people have left the stair with three on the flight and one on the half landing, 1 s after (c).



(e) Three people have left the stair with two on the flight and one on the half landing, 1 s after (d).

(f) Four people have left the stair with two on the flight, 1 s after (e).

(g) Four people have left the stair with two on the flight, 1 s after (f).



(h) Four people have left the stair with two on the flight, 1 s after (g).

Figure 77. Group of six descending the temporary scaffold stairs in Trial 4.

This type of analysis was undertaken for all the identified groups in the video sequences studied. The results of the analysis are presented in Table 14 with the full results presented in Appendix 4. The spacing frequency is presented in Figure 78 while the frequency distribution for the number of people on the flight is presented in Figure 79.

Table 14. Summary of interpersonal spacing on stair flight for Trial 4.

Parameter	Data
Alarm time (hh:mm:ss)	09:30:59
Start time of analysis (hh:mm:ss)	09:31:56
End time of analysis (hh:mm:ss)	09:48:56
Number of groups observed	32
Minimum group size	2
Maximum group size	8
Mean group size	3.3
Number of individual workers observed	104
Number of individual spacing measurements	192
Minimum spacing observed	1
Maximum spacing observed	6
Mean spacing observed	2.5
Minimum number of workers on stair flight	1
Maximum number of workers on stair flight	4
Mean number of workers on stair flight	2.2

From Figure 78 it can be seen that modal stair spacing is 2 (91 occurrences representing 47% of the data), with the next most common stair spacing being 3 (51 occurrences representing 27% of the data). Presented in Figure 79 is a frequency distribution for the number of people on the flight at any one time. As can be seen, the modal number of people to occupy the flight is 2 (74 occurrences representing 45% of the data), with the next most common occupancy being 3 (56 occurrences representing 34% of the data). The maximum number observed on the flight is 4, with just 2 occurrences representing 1% of the data.

Unlike in Trial 2, there are sufficient data points in Trial 4 to undertake a more detailed analysis. In Figure 80 we present the frequency distribution for the interpersonal spacing when there are at least three people on the flight. With more than two people on the flight the available space between occupants is more constrained and so provides a better representation of the likely minimum preferred spacing distance between stair occupants. We note that while occupants can get down to a spacing of 1 tread (17%), this represents a very low proportion of the observed interpersonal spacing distances. The modal interpersonal distance is 2 treads (53%) while the next most common spacing is 3 treads, but this represents only 23% of the observed spacings.

As noted in the analysis of the Trial 2 data, when based on the entire data-set (for Trial 4), the flight occupancy analysis is biased by the high number of small groups present in the data. If we restrict the analysis to groups consisting of 3 or more workers, we have a better representation of the most likely maximum occupancy for the flight (see Figure 81). In this case, the most common number of people to occupy the flight is 3 (52%) with the next most common occupancy being 2 (34%). A flight occupancy of 3 is consistent with an interpersonal spacing of 2. While 4 people have occupied the flight at one time, this only represents 2% of the cases and so is a low likelihood event. Thus, for groups with 3 or more people, the most common maximum occupancy for the flight is 3.

From the Trial 4 data, the minimum preferred spacing is 2 treads in situations where there are 3 or more people attempting to occupy a flight simultaneously and the maximum likely occupancy of the flight is 3.

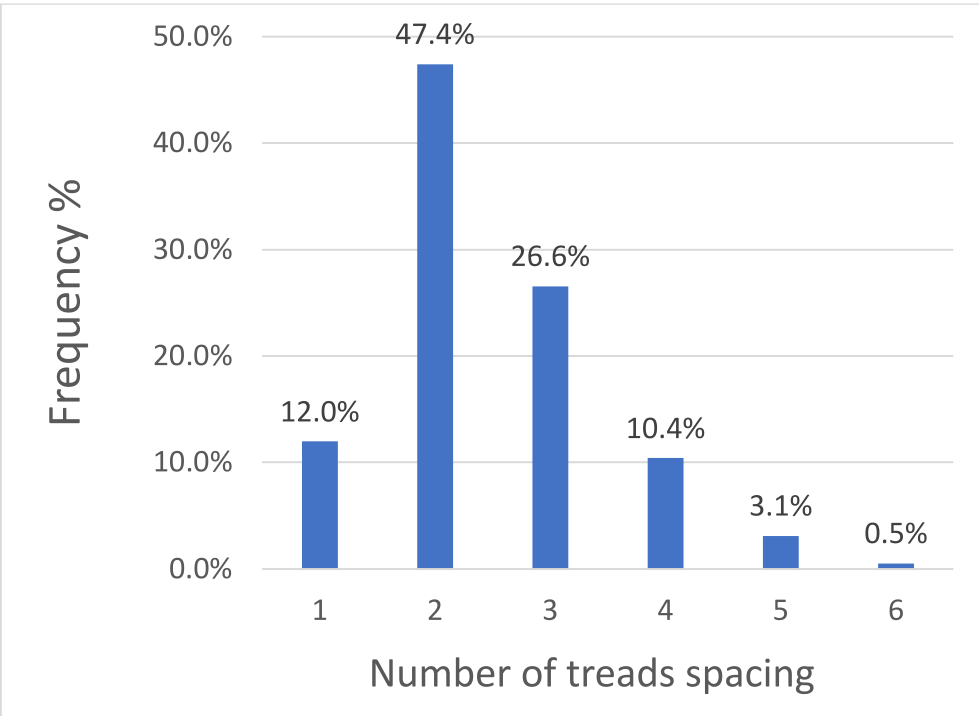


Figure 78. Occupant spacing on flight for Trial 4.

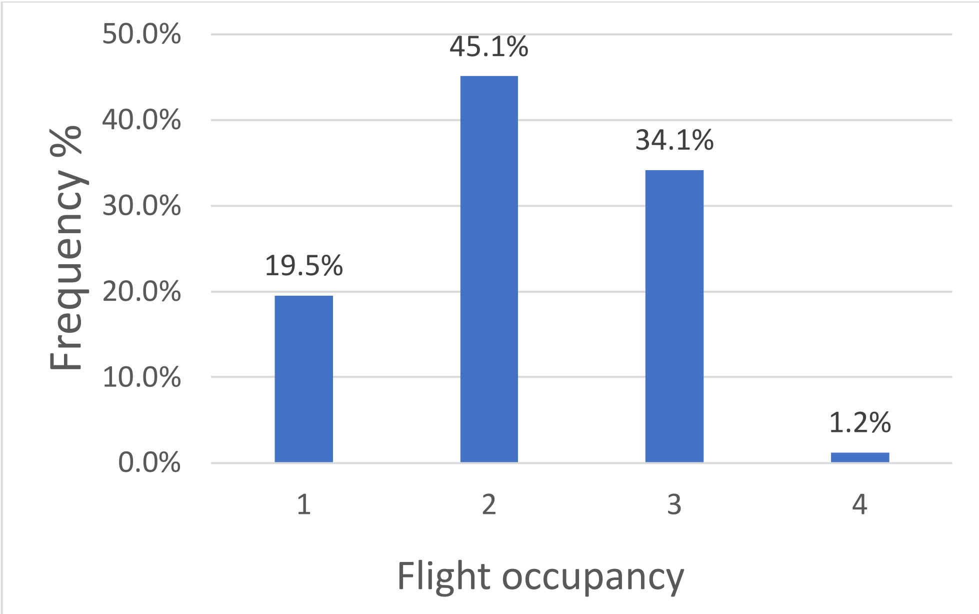


Figure 79. Flight occupancy for Trial 4.

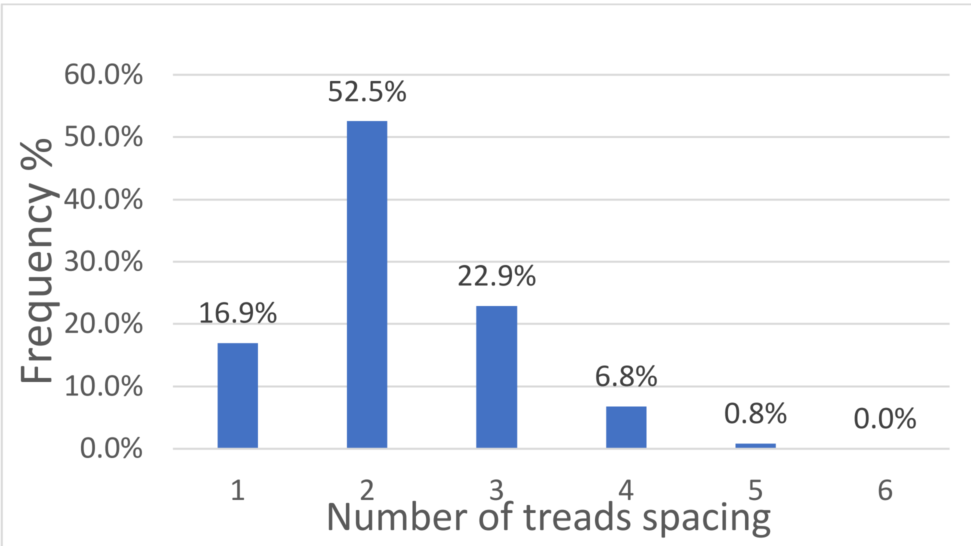


Figure 80. Stair spacing frequency when three or more workers occupy the flight for Trial 4.

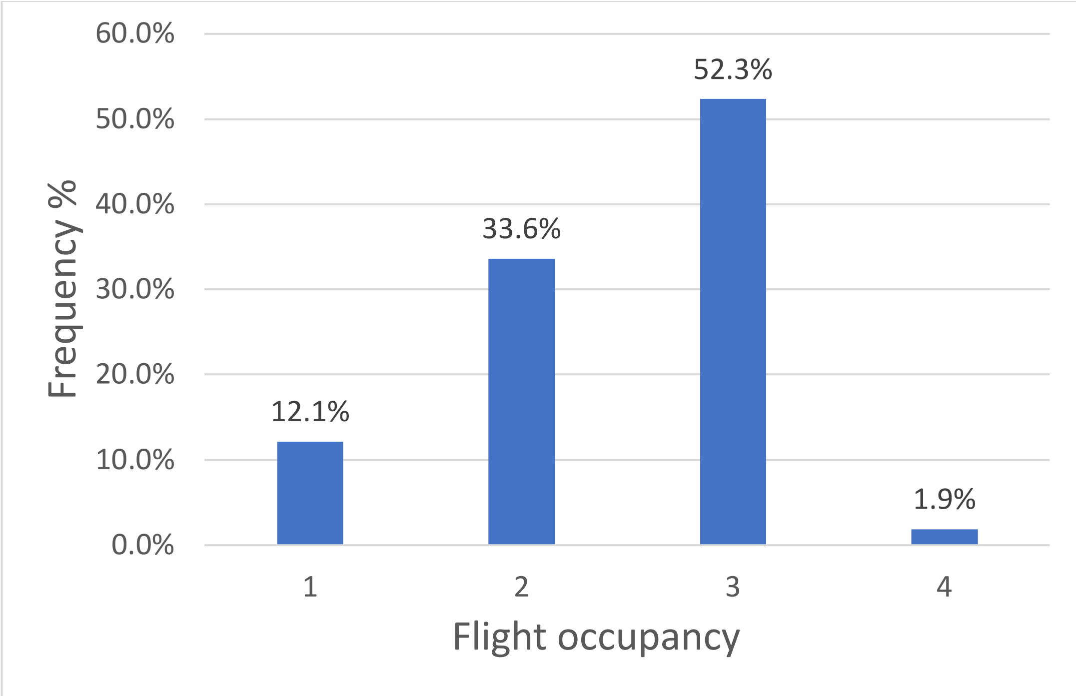


Figure 81. Stair occupancy frequency for groups with three or more workers in Trial 4.

Finding 4.8: A single flight of a single-lane temporary scaffold dogleg stair with nine treads per flight was monitored during the Trial 4 evacuation and it was noted that 135 people passed through the flight. The most frequent spacing between occupants when there are three or more on the flight was two treads and the most common number of people that was accommodated on the flight was three for groups consisting of three or more people. The observed spacing is significantly different to that found on regular building stairs, which is typically one tread between occupants. The lower interpersonal spacing on the temporary stair will have a negative impact on the flow capability of the stair, essentially decreasing the flow compared to a permanent stair of similar width.

4.5 Combined questionnaire analysis

In total 920 workers evacuated from within the high-rise buildings during all four trials. A total of 76 questionnaires (full or partially completed) were collected from the trials (32 from Trial 1, 34 from Trial 2, 10 from Trial 3 and 0 from Trial 4), representing a return rate of 8.3%. Of these, 15 were excluded (4 from Trial 1, 1 from Trial 2 and 10 from Trial 3) from the analysis due to either the extent of the missing data or because they contained comments showing the participants did not take the questions seriously. As a result, there were 61 questionnaires used for the analysis in this report, which allowed for some meaningful statistics to be calculated, but represents only 7% of the population that evacuated.

As there were only a small number of questionnaires returned from just two trials, the two sets of trial questionnaires have been merged. Although the questionnaires from Trial 2 were significantly shorter, they still shared many of the same questions (other questions were stripped out of the questionnaires from Trial 1 and thus cannot be used).

4.5.1 Demographics

From the questionnaires there was a wide range of ages, from teenagers to people in their 60s, but the majority of the participants were aged between 25 and 44 (see Figure 82). Since there was a low frequency of older workers in this sample, no further analysis was done on the effect of age (i.e. in relation to reliance on devices such as hoists).

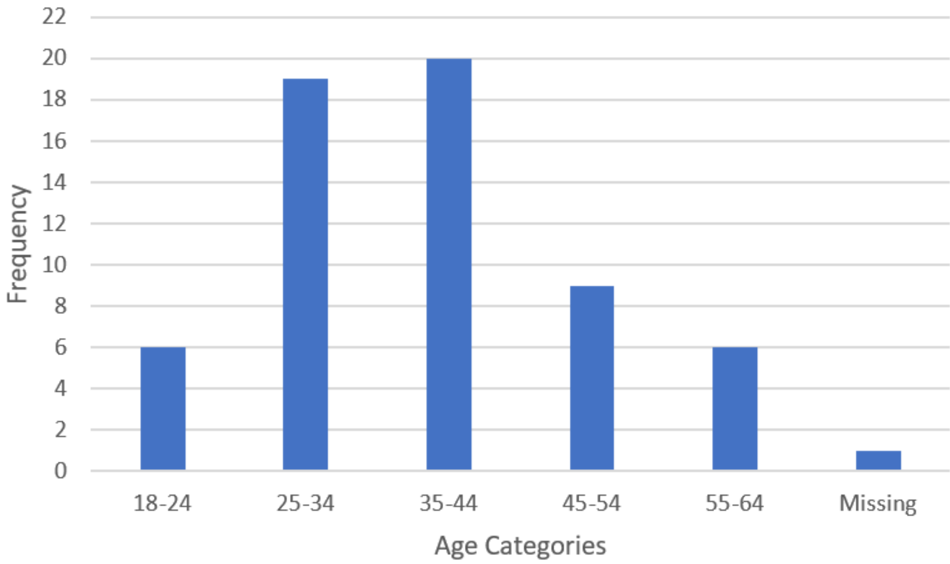


Figure 82. Age demographic of the participating workforce.

English was the first language of 39% of participants. The remaining 61% nevertheless tended to report that they could both speak and read English "well". A Pearson's Chi-Square Test found a significant difference in whether participants' first language was English or not according to the construction site ($\chi^2(1) = 6.87$, $p = 0.009$). In other words, there were more native English speakers in Trial 1 at 100 Bishopsgate than in Trial 2 at 22 Bishopsgate. It is also noted that the number of Romanian questionnaires completed was 19% in Trial 1 and 18% in Trial 2.

Workers had worked at their construction site (either 100 Bishopsgate or 22 Bishopsgate) from less than one week to up to 72 months (as denoted by the 'other' option in the questionnaire) but most frequently the participants had worked there for less than six months, showing a workforce which is relatively unfamiliar with the workplace (see Figure 83).

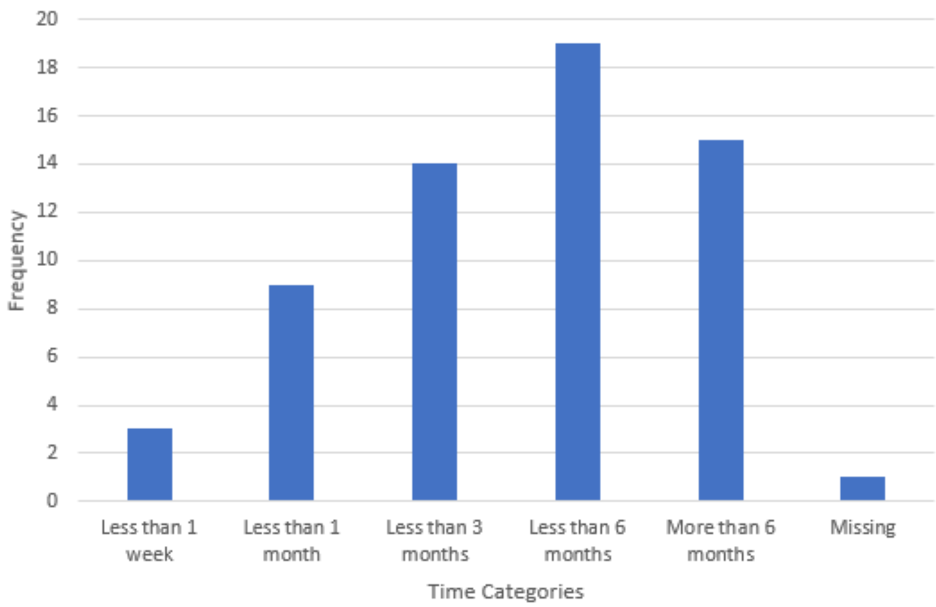


Figure 83. Experience of the participating workforce.

Key Finding 5.1: Survey demographics – Correctly completed questionnaires were received from 7% (61 participants) of the population that evacuated during the four trials, with all the data being generated from Trial 1 and Trial 2. However, the data does represent information from 27% of the people who evacuated from these two trials. Concerning the demographics of the questionnaire participants:

- ***the majority (64%) were aged between 25 and 44 years of age with 25% over 44 years of age***
- ***the majority of participants (61%) did not have English as their first language***
- ***the majority of participants (75%) had been on the construction site for less than six months, with 20% having been on the site for less than one month, suggesting that a sizeable number of workers may not have been fully familiar with the workplace.***

Participants were reportedly spread across several levels, with more workers on a floor in Trial 1 and more workers on the ground floor in Trial 2 (as seen in Table 15). There were also eight workers located in basements across both trials. It is noted that no specific questions in the questionnaire related to the basement environment.

Table 15. Reported starting locations of participating workers.

Trial 1			Trial 2	
Area	**Frequency**		**Area**	**Frequency**
Jumpform	4		Jumpform	1
Core	5		Core	6
Floor	11		Floor	3
Other: Scaffold	2		Other: Unspecified/Hoist	4
Ground	3		Ground	12
Basement	2		Basement	6
Missing	1		Missing	1

4.5.2 Normal ingress/egress

Overall, for their normal circulatory movement around the site, participants most frequently used a combination of stairs and hoist (48%) or stairs alone (36%) to travel up and down on their site. This suggests that the participants were very familiar with the location of the stairs.

- Stairs + Hoist = 48% (29)
- Stairs Always = 36% (22)
- Hoist Always = 5% (3)
- Other = 8% (5)
- Missing = 3% (2)

A Fisher's Exact Test found no significant differences between construction sites in terms of how participants normally travelled up and down on their site ($p = 0.391$).

4.5.3 Believability of alarm

Overall, the vast majority (97% – 59) of participants heard the site alarm before they started to evacuate. When looking at the question relating to the believability of the alarm, almost two-thirds of the participants (62%) reported that they thought it was a real emergency when they heard the alarm sound, compared to 33% who believed it was not a real emergency. 5% of the participants did not answer this question. A Pearson's Chi-Square Test detected a significant difference in whether participants thought it was a real emergency or not according to the construction site ($\chi^2(1) = 9.00$, $p = 0.003$).

During Trial 1, over half of the sample (56%) were sceptical as to whether it was a real emergency, whereas in Trial 2 around four-fifths of the sample (82%) believed it was a real emergency.

Key Finding 5.2: Response to alarm 1 – The vast majority (97%) of participants heard the alarm with the majority (62%) believing that the alarm was a real emergency, suggesting that the workers' behaviour during the trials may be representative of how they would react in a real emergency. Furthermore, while not perfect, the volume of the alarm on the two sites appears to have been adequate given that 97% of the respondents reported hearing the alarm.

4.5.4 Evacuation procedures

In the questions probing the participants' knowledge of the evacuation procedures, 82% of the participants knew the correct procedure was to evacuate immediately upon hearing the site alarm.

However, while the vast majority of workers understood that they should commence evacuation immediately, only 49% reported that their first action upon realising something was happening was to start evacuating, with 21% (13) reporting they alerted others (information task), 8% (5) reporting they shut down/secured machinery (action task), 7% (4) sought more information (information task) and 3% (2) completed their pre-alarm task (re-engage in pre-alarm activity). This finding is supported by the video evidence which suggests that in 48% of the collected data for Trials 1, 3 and 4, the workers rapidly (less than 40 s) disengaged from their pre-alarm activities and once disengaged, in 41% of the cases undertook at most one task before starting their evacuation movement phase (see Section 4.6.3). While a significant number of people knew the evacuation procedures (82%), fewer than 50% actually followed through with the procedures. The video evidence suggests that almost a third (32%) of the participants across the trials (for which we have response phase data), took longer than 60 s to disengage from their pre-alarm activities with almost a quarter (23%) undertaking many (four or more) tasks once disengaged and prior to evacuation (see Section 4.6.3). This suggests that better training or greater enforcement through supervisors is required.

Key Finding 5.3: Response to alarm 2 – More than four-fifths (82%) of the participants knew that they were supposed to evacuate immediately on hearing the alarm but only half (49%) reported that their first action upon hearing the alarm was to start to evacuate. This result is supported by the video evidence which suggests that many of the workers delayed the start of their evacuation in order to complete their tasks, to shut down a task or pack up equipment. One possible explanation for the difference between knowing the requirement and following through with the requirement is that it is not clear what is precisely meant by 'evacuate immediately', i.e. workers may believe that by responding to the alarm (in ways other than evacuation movement) this nonetheless counts as commencing evacuation immediately. This suggests that better training or greater enforcement through supervisors is required.

Furthermore, the most frequent means of finding an exit route (33%, 20) during the evacuation was by recalling the evacuation diagram, with the second most frequent action being to look for an emergency exit sign (21%, 13) (rather than following others (13%, 8), taking the same route as they entered on (10%, 6) or looking to an authority figure (3%, 2)).

A series of Pearson's Chi-Square Tests detected no significant associations between participants' first language and whether or not they knew the correct evacuation procedure ($\chi^2(1) = 0.92$, $p = 0.338$), evacuated immediately ($\chi^2(1) = 1.90$, $p = 0.168$), or recalled the evacuation diagram ($\chi^2(1) = 0.25$, $p =$

0.620). In other words, non-native English speakers responded no differently to native English speakers on questions about evacuation procedures.

A further Chi-Square Test did detect a significant association between the site and whether or not participants recalled the evacuation diagram ($\chi^2(1) = 4.41$, $p = 0.036$), i.e. workers at 22 Bishopsgate were more likely to recall the diagram than workers at 100 Bishopsgate, but the two sites did not differ significantly in terms of the length of time workers had been at their site (Mann-Whitney Test: $U = 356.50$, $p = 0.172$), so this association cannot be attributed to differences in experience and therefore familiarity with the exit routes.

Key Finding 5.4: Wayfinding – A third of participants (33%) stated that they knew the exit route while a fifth (21%) stated that they looked for emergency exit signage and very few simply followed others or looked for an authority figure to direct them, and it is noted that there was no significant difference between native and non-native English speakers. However, there was a statistically significant difference in exit route knowledge between sites (22 BG better than 100 BG); this may suggest that local site policy and procedures (safety culture) may impact worker knowledge of evacuation procedures. Furthermore, the high proportion of workers that relied on exit signage highlights the importance of having up-to-date and prominent emergency exit signage on site.

4.5.5 Task importance

When asked to rate how important it was to finish their pre-alarm task before starting to evacuate, participants tended to believe that their employer would think it slightly more important than they did personally.

- Self: median rating = 1.00 [“Not at all important”], IQR = 1.00–3.00
- Employer: median rating = 1.50 [“A little important”], IQR = 1.00–3.00

A Wilcoxon Signed Ranks Test detected a significant difference in task importance ratings depending on the perspective adopted, i.e. self versus employer, $Z = -2.44$, $p = 0.015$.

Mann-Whitney U Tests detected no site differences in task importance ratings for self ($U = 264.50$, $p = 0.083$), but did detect a significant difference for employer ($U = 215.00$, $p = 0.016$), i.e. participants in Trial 2 were more likely to give higher importance ratings when answering from the perspective of their employer than were participants in Trial 1. This implies that workers at 22 Bishopsgate perceived somewhat greater work pressure. However, if they did then this did not result in workers delaying evacuation as there was no significant association detected between site and whether participants evacuated immediately or not (Pearson’s Chi-Square Test: $\chi^2(1) = 0.06$, $p = 0.813$).

Key Finding 5.5: Task importance – Workers perceive that employers find it more important than they do to complete their tasks prior to evacuating, suggesting improvements in local safety culture may be desirable. Furthermore, there was a statistically significant difference between trials, suggesting that workers at 22 BG perceived a higher pressure to complete tasks than those at 100 BG. This may be related to the progress of work on both sites.

In addition, this perception may be sending mixed messages to the workers regarding the need for rapid evacuation, hence explaining the observation that while 82% of the workers understand the need to evacuate immediately only 49% did so (see Key Finding 5.3). This reinforces the suggestion of the need for better training and improvements in local safety culture.

4.5.6 Evacuation trigger

When asked what prompted them to leave, most of the participants (80%) said the alarm, indicating that the alarm was the most effective method to get everyone to start evacuating. However, the video analysis (see Section 4.1) suggests that 46 workers in Trial 1 required a supervisor intervention before they decided to commence evacuation. It is not clear how many workers in Trial 2 required a supervisor intervention to start the evacuation process as this could not be clearly determined from the video footage. While it is clear that the two supervisors in Trial 2 are intervening with all the workers, it is uncertain how many of the 28 workers had already started to evacuate. If we assume none of the workers in Trial 2 required a staff intervention, this would mean 46 workers out of 108, or 43%, had not started their evacuation shortly after the sounding of the alarm and so required a staff intervention. Conversely, if we assume all 28 workers in Trial 2 required a staff intervention, this would mean 76 workers out of 108, or 70%, required a staff intervention to start their evacuation. If we only consider the Trial 1 workers, then a total of 57% of observed workers required supervisor intervention to start their evacuation. All these values bring into question how reliable the answers to this question were. The caveat here is that the workers who filled in the questionnaires may not necessarily have been the same workers for whom a response time was extracted (as there were a total of 230 workers who evacuated in Trials 1 and 2, 61 questionnaires returned and only 110 response times extracted from the video analysis for Trials 1 and 2). The large number of supervisor interventions suggests that better training emphasising the need for rapid evacuation is required and possibly more supervisors on site who can intervene and encourage workers to rapidly commence their evacuation.

Key Finding 5.6: Response to alarm 3 – Four-fifths (80%) of the participants claim they were prompted by the alarm and did not require a staff intervention to commence their evacuation. However, this is not supported by the video analysis which suggest that between 43% and 70% of the workers required a staff intervention to commence their evacuation. These differences may be due to small numbers in both the survey and video analysis.

4.5.7 Risk-taking, risk perception

The questionnaires indicated that the workers tended not to be high risk-takers. The rating scores that participants gave for each of the nine items on the risk-taking measure were summed and, out of a possible range of 9 to 63, the mean summed score was 27.41 (standard deviation = 13.16). So, in other words, participants tended to score more in the lower half of the possible range rather than towards the high end. To put this into further context, participants' ratings scores for the six items that were also in the Hulse et al. scale [94] (see Section 3.5.3) were summed and it was found that the mean summed score was 18.23 (standard deviation = 9.36) out of a possible range of 6 to 42. This is slightly (but not significantly) lower than that found by Hulse et al. in their UK study [94] with almost 1,000 members of the general public (mean = 19.62, standard deviation = 6.61); Independent Samples T-Test: $t(953) = 1.26$, $p = 0.208$. So, despite working in an environment that might objectively be considered more dangerous than that experienced daily by most members of the public, the workers did not display any greater willingness to take risks than the average person.

Key Finding 5.7: Risk perception 1 – Construction site workers, despite working in an inherently dangerous environment (with an average fatality rate four times that of land-based industries in general (see Section 1.1)), appear to have the same appetite for risk as the average person, i.e. they are not more inclined to take risks than the average person.

When asked to rate the level of danger they sensed at the point when the alarm sounded during their trial, the majority of workers (52% – 32) reported that they were "not at all" in any danger, i.e. the lowest level of perceived danger (point 1 on a 4-point scale). Only 16% (9) reported that they sensed some level of danger, with almost a third (31% – 19) not answering the question. This perception did not change substantially when the participants started their evacuation. While this might seem strange given that the majority of participants believed it was a real emergency, such a low level of perceived risk is put into context by the fact that (a) there were no tangible hazards such as smoke or flames present in their environment, and (b) only one participant reported sensing that they were in "extreme danger", i.e. the highest level of perceived danger (point 4 on a 4-point scale), on their construction site under normal (non-emergency) conditions, while everyone else gave a much lower perceived risk rating. These results suggest that participants perceived their site to be a safe environment at all times.

Participants perceived their own construction site to be less risky than construction sites in general (it is noted that some 36% (22) workers did not reply to this question). Most workers (41% – 25) sensed that they were "not at all" in danger on their own construction site (i.e. the lowest level of perceived danger (point 1 on a 4-point scale)) with 23% (14) sensing some level of danger (the other three categories). However, when asked about construction sites in general, most workers (34% – 21) sensed some level of danger (the other three categories) while 28% (17) sensed no level of danger. A McNemar Test found this difference to be significant: p = 0.031.

Key Finding 5.8: Risk perception 2 – Construction site workers perceive that they are in a safe environment while on their construction site. This is a somewhat surprising finding given that construction sites are inherently dangerous environments (with an average fatality rate four times that of land-based industries in general (see Section 1.1)). Furthermore, there was a statistically significant difference in the level of safety perceived by workers on the Multiplex construction sites compared with their perception of safety on construction sites in general. While the high level of perceived safety on Multiplex sites is a credit to the safety culture developed by Multiplex, if workers are not also aware of, and alert to, the inherent dangers of a construction site this may lead to a level of complacency in their response to potentially hazardous situations that may develop.

For example, while most workers believed that the alarm represented a "real" emergency incident, they also felt that they were in "no danger". If we also take into consideration the workers' perception that their managers would prefer them to complete their tasks prior to evacuating, this may explain some of the long response times observed during the trials. One way of tackling this complacency is through training and developing an understanding of how quickly an emergency situation can deteriorate, reinforcing the message that it is essential to disengage immediately from pre-alarm activities when an alarm is sounded and what immediately means – emphasising the point that in an emergency, every second counts.

4.6 Combined response time data analysis

In this section we attempt to combine the response time data generated by four full-scale evacuation trials in order to generate a generalised RT distribution that can be used for construction sites. The four full-scale unannounced evacuations involved the evacuation of some 926 workers. Of the 926 workers exiting the buildings, 270 response times were extracted from the video footage, of which 88 response times were derived for workers initially located in the formworks at the time of the alarm (Table 16). It is noted that when Trial 3 was conducted, 100 BG had reached its maximum height and so there were no formworks.

Presented in Table 17 is a summary of the RT distributions collected during the trials.

Two trials involved evacuations in which workers were located in both the formworks and the rest of the building at the time of the alarm: Trial 1 involving 100 BG and Trial 4 involving 22 BG. One trial,

Trial 2 (22 GB), only involved the formwork while one trial, Trial 3 (100 BG), only involved the main building. The analysis will focus on the RT distributions for the formworks separately from the RT distribution for the main building.

Table 16. Summary of the data collected from the four high-rise construction site evacuation trials.

Trial	Building	Date	Number of workers exited	Number of response times collected	Number of workers in the formworks
1	100BG	Feb-17	184	106*	20
2	22BG	Feb-17	46	30	30
3	100BG	Oct-17	308	52	-
4	22BG	Nov-17	388	82	38
Total			**926**	**270**	**88**

*: includes 26 workers on the ground floor.

Table 17. Summary of response time data for the four unannounced high-rise construction site evacuations.

Trial	Building/ date	Number of Floors^{xx}	Region	Min (s)	Max (s)	Average (s)	Standard deviation
1	100 BG Feb 17	19 core 12 floors	Formwork^{x}	0.2	50.7	28.9	16.4
			Formwork*	7.7	64.8	42.2	17.8
			Main++	8.8	203.8	76.4	56.9
			All$^{x,++}$	0.2	203.8	65.0	55.6
2	22 BG Feb 17	13 core^{+*} 0 floors	Formwork	12.2	114.7	55.6	23.4
			Main	-	-	-	-
			All	-	-	-	-
3	100 BG Oct 17	38 core 33 floors	Formwork	-	-	-	-
			Main	0.9	191.2	61.6	47.1
			All	-	-	-	-
4	22 BG Nov 17	32 core^{+*} 20 floors	Formwork+	4.8	247.7	75.4	51.6
			Formwork**	4.8	133.2	58.4	32.6
			Main	9.0	340.2	75.3	73.1
			All**	4.8	340.2	75.3	64.0

x: from alarm 2; *: from alarm 1; +: including 6 supervisors; **: excluding 6 supervisors; ++: excludes 26 workers on ground floor; xx: excluding the formworks; +*: North Core only.

4.6.1 Response time distributions for the formworks

In this section the data from Trials 1, 2 and 4 will be considered as these are the only ones that involve workers located in the formworks at the time of the alarm.

The analysis in this section will explore the RT distributions to establish the following:

- nature of the curve describing the response time probability distributions
  - does the formworks RT distribution follow the usual lognormal distribution or the normal distribution?
- impact of height on the response time probability distributions
  - does the height of the formwork impact worker response time? If so, in what way?
- impact of work type on the response time probability distributions
  - does the nature of the work and hence phase of construction impact worker response time?

- development of a generalised response time probability distributions
    - can we specify a generalised or several generalised RT distribution(s) for workers in the formworks? If so, how general are these relationships?

4.6.1.1 Nature of the curve describing the response time probability distributions

When analysing the RT distributions it was noted that the general shape of the formworks RT distribution did not appear to be lognormal but normal in appearance. Statistical analysis was undertaken on the raw data to determine whether or not the data could be described using a normal distribution and if so, to determine the form of the distribution and the goodness of fit. The software package 'IBM SPSS Statistics 25' was used to undertake the statistical testing.

The Shapiro-Wilks test was performed to test for normality of the distributions. In this test, if the p-value returned was higher than 0.05 then the distribution could be said to follow a normal distribution. The test revealed that the distributions for Trial 1 (slipform) and Trial 2 (jumpform) were indeed normal in nature, returning results of p=0.083 for the slipform in Trial 1, and p=0.167 for the jumpform in Trial 2. However, the distribution for Trial 4 returned a p-value of 0.006 which suggests that the distribution is not normal in nature.

In Section 4.4.1 it was noted that in Trial 4 the final six people to exit the formworks were supervisors who delayed their response and self-evacuation until all the workers in the formworks had evacuated. In describing the RT distribution for the formworks, these six supervisors should be removed as their behaviour is not typical of workers in the formworks. With these six data points removed, the distribution looks more normal (see Figure 73 in Section 4.4.1) and so was again tested using the Shapiro-Wilks test. Removing these six response times from the RT distribution for Trial 4 and repeating the Shapiro-Wilks test returns a value of p = 0.26, thus demonstrating that the formwork distribution in Trial 4 is normal.

Presented in Figure 84–Figure **86** are the data-sets with best-fit normal distributions with the equations (generated using Microsoft Excel 365) describing these presented in Equations 2 to 4.

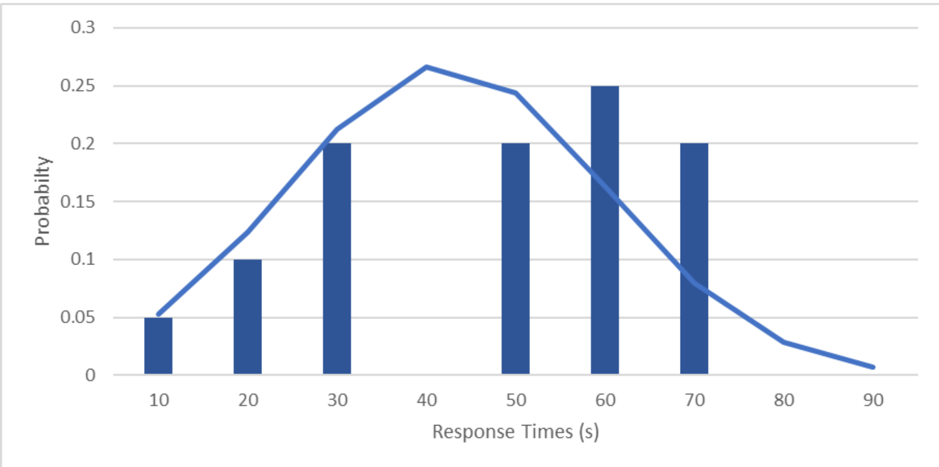


Figure 84. Slipform response time distribution from Trial 1 with fitted normal curve.

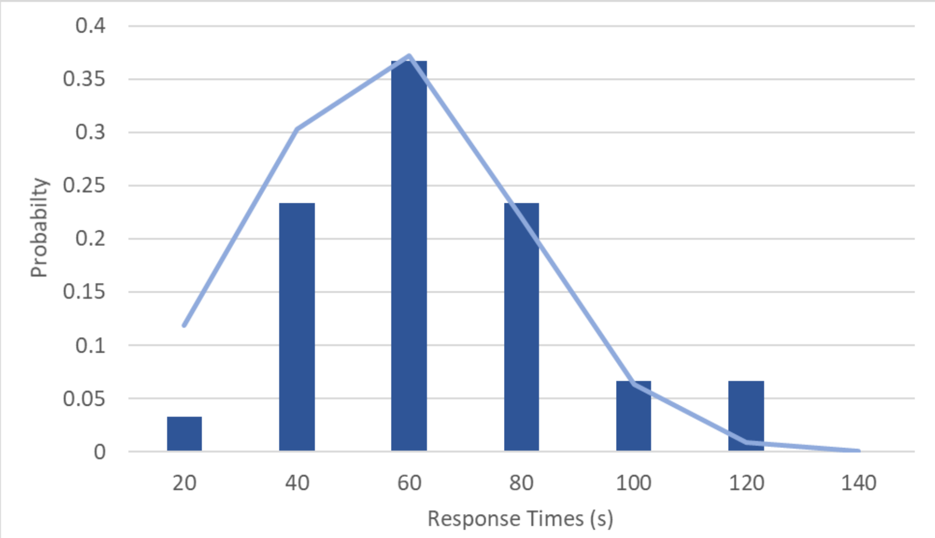


Figure 85. Jumpform response time distribution for Trial 2 with a fitted normal curve.

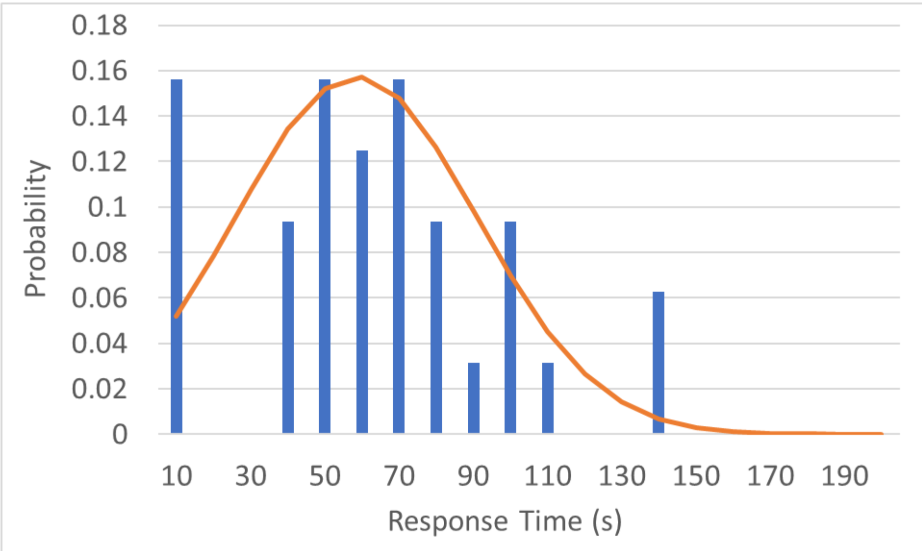


Figure 86. Jumpform response time distribution for Trial 4 with a fitted normal curve.

$$f(t) = \frac{1}{16.4\sqrt{2\pi}} \exp\left[-\frac{(t - 28.9)^2}{2 * 16.4^2}\right] \quad (2)$$

Where 0.2 < t (response time) < 50.7, the mean is 28.9 and the standard deviation is 16.4.

$$f(t) = \frac{1}{23.4\sqrt{2\pi}} \exp\left[-\frac{(t - 55.5)^2}{2 * 23.4^2}\right] \quad (3)$$

Where 12.2 < t < 114.7, the mean is 55.5 and the standard deviation is 23.4.

$$f(t) = \frac{1}{58.4\sqrt{2\pi}} \exp\left[-\frac{(t - 57.08)^2}{2 * 32.6^2}\right] \quad (4)$$

Where 4.8 < t < 133.2, the mean is 57.08 and the standard deviation is 32.6.

Key Finding 6.1: Nature of RT distribution for formworks – The response times for workers in the formworks can be represented using a normal distribution. This is different to the usual representation of response times which is lognormal in nature. This relationship has been observed for three different unannounced full-scale evacuation trials conducted on two different high-rise construction sites.

4.6.1.2 Impact of height on the response time distributions for workers in the formwork

Apart from the usual factors that influence response time, such as type of alarm, being isolated and staff intervention, it is reasonable to assume that response time for workers located in the formwork may be dependent on the height of construction and the nature of the work being undertaken at the time of the alarm, which in turn is dependent on the phase of construction.

Here we explore the impact of height of the formworks on worker response times. When exploring the impact of height on response behaviour for workers in the formworks it is important that the same type of activity is being undertaken at the time of the evacuation in order to ensure that only one key influencing parameter is being investigated. Of the three evacuations involving formworks, Trials 2 and 4 (both 22 BG and both using a jumpform) involved formwork workers undertaking similar tasks, i.e. associated with fixing rebar ahead of a scheduled concrete pour, and so these two trials can be used to explore the impact of height on response time. Fortunately, at the time of Trial 2, the core was at Level 13 with the jumpform at Level 14 (top deck of the jumpform at Level 15) and at the time of Trial 4 the core was at Level 32 with the jumpform at Level 33 (top deck of the jumpform at Level 34). The top deck of the jumpform in Trial 4 was 2.3 times higher than in Trial 2. Comparing the RT distributions for Trial 2 (Figure 59) and Trial 4 (Figure 72) we note that while the distributions look similar, the response times in Trial 4 are considerably longer than those in Trial 2 (see Figure 87).

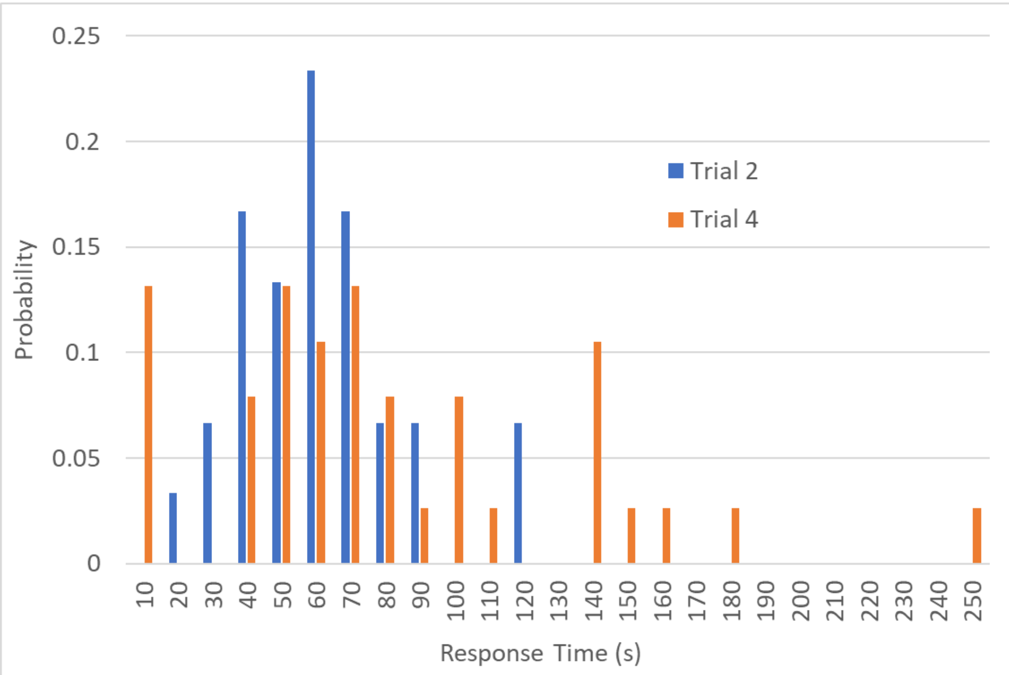


Figure 87. Comparison of jumpform response times from Trial 2 and Trial 4.

However, as noted earlier (see Sections 4.4.1 and 4.6.1.1) the long response times in Trial 4 are due to six supervisors that delayed the start of their evacuation until the jumpform was clear. In Trial 2, there were two supervisors, but their role was simply to alert the workers to evacuate and then to self-evacuate immediately (see Section 4.2.1). If we remove the six supervisors from Trial 4, and to be consistent, the two supervisors from Trial 2, the RT distribution for the formworks for the two trials appears as shown in Figure 88. It is noted that the Shapiro-Wilks test confirms that the Trial 2 distribution with the two supervisors removed is still normal (p = 0.11). Visual inspection of these two distributions suggests that they are both normal in appearance and very similar. Furthermore, comparing the minimum, mean and maximum values for these two distributions suggest that they are very similar (see Table 18).

Table 18. Summary of Trial 2 and Trial 4 jumpform response times.

Supervisor status	Trial (22 BG)	Min (s)	Max (s)	Mean (s)	Number of staff	Height level*
with	Trial 2	12.2	114.7	55.6	30	15
	Trial 4	4.8	247.7	75.4	38	34
without	Trial 2	12.2	114.7	55.2	28	15
	Trial 4	4.8	133.2	58.4	32	34

*: Top deck of jumpform.

To determine how similar the two distributions are, the independent two tailed t-test was performed. For this test, if the returned value of p is greater than 0.05 then the two distributions are said to be of the same distribution and can therefore be merged. The t-test returned a value of p = 0.705. This result suggests that the two data-sets are derived from the same distribution.

This is an important observation as it suggests that for construction sites up to 34 floors in height, the response time of workers in the formworks is not impacted by the height of the construction. This observation may be the result of the workers' perception that they are not at risk while on the construction site (see Section 4.5.7). It remains to be seen if the same observation is true for workers located in the bulk of the building.

Key Finding 6.2: Impact of height on formworks RT distribution – Two independent evacuation trials from two high-rise construction sites with jumpforms at Levels 14 and 33, involving 28 and 32 workers respectively involved in similar activities just prior to a concrete pour, suggest that the response time distribution is not impacted by height. This suggests that for high-rise construction sites with formworks located at up to 33 levels, the response times for workers located in the formworks are not impacted by the height of construction. This observation may be the result of construction workers not perceiving that they are at risk while on the construction site.

The time for the supervisors to disengage from their pre-alarm activities and begin to alert the workers in the jumpform is presented in Table 19. It was not possible to measure the disengagement time for the supervisors in Trial 2 and so only the times for Trial 4 are presented. Here we note that the mean time for the supervisors to disengage from their pre-alarm activities and commence encouraging the workers to start their evacuation is 5.9 s. This is a useful statistic as it not only demonstrates how quickly well-trained and motivated supervisors can disengage from their pre-alarm activities, it also provides a useful evidence base for modelling purposes, should it be necessary to specifically model the behaviour of supervisors. Furthermore, it is useful to note that these disengagement times are associated with supervisors who are engaged in high-priority work activities within the formworks prior to a concrete pour.

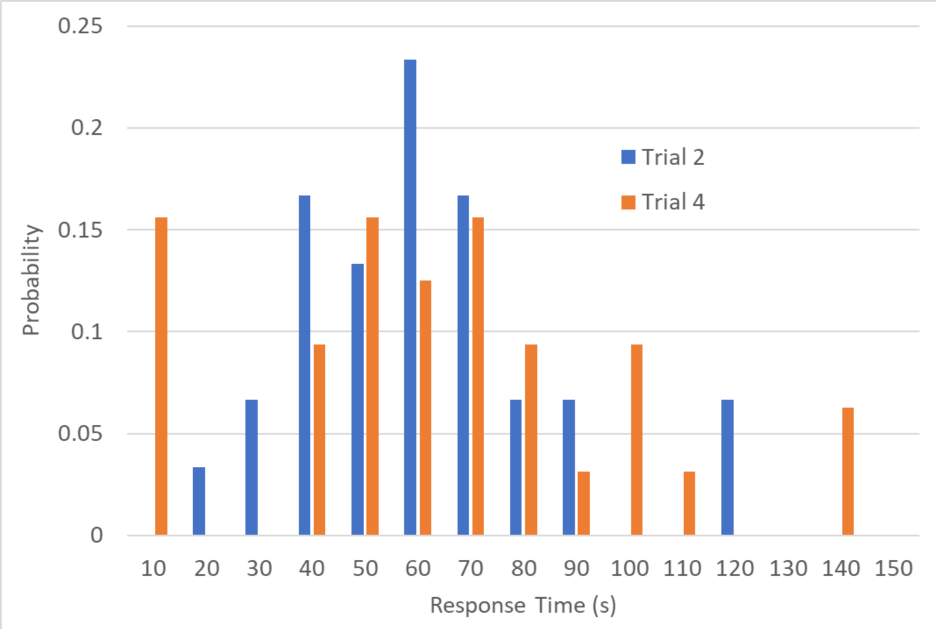


Figure 88. Comparison of jumpform response times from Trial 2 and Trial 4, excluding supervisors.

Table 19. Summary of disengagement times for supervisors in Trial 4 formworks.

Trial	Min (s)	Max (s)	Mean (s)	Number of supervisors
Trial 4	2.1	16.8	5.9	6

Key Finding 6.3: Supervisor disengagement time within the formworks – The average time for supervisors within the formworks engaged in high-priority activities prior to a concrete pour to disengage from their pre-alarm activities on sounding of the fire alarm is 5.9 s (data from six supervisors). This extremely rapid disengagement is an example of the performance of well-trained and highly motivated staff.

4.6.1.3 Impact of work type on the response time distributions

The second key parameter that has been suggested to impact worker response times within the formworks is the nature of the work being performed at the time of the alarm (see Section 4.4). While all work undertaken in the formworks is important in keeping the development of the building on schedule, some work is more time-sensitive than others. For example, as the time for the next concrete pour approaches, it is essential that workers complete all their tasks such as installing rebar as quickly as possible, as any last-minute rescheduling of concrete pours can be expensive and very disruptive to the building schedule. It is reasonable to assume that workers involved in these activities are likely to be highly focused on their tasks and so, during an evacuation alarm, are likely to exhibit delays in disengaging from their pre-alarm activities and engaging in evacuation behaviours, prolonging response times.

In contrast, after a successful concrete pour, the activities in the formworks are less time-critical as the workers dismantle or reshape the formwork in preparation for the next round of rebar fitting and the next concrete pour. Delays incurred during these activities are less likely to be so critical. As a result, it is suggested that workers involved in these activities are more likely to rapidly disengage from pre-alarm activities and engage in evacuation behaviours, producing relatively shorter response times. Furthermore, given the focused nature of the work undertaken within the formworks, it is likely that predominantly one type of activity will occur at any one time, and so depending on the phase of construction, formworks workers are likely to be relatively rapid or relatively long responders.

When exploring the impact of work type on response behaviour for workers in the formworks, it is important that the same, or very similar, height of construction at the time of the evacuation is considered to ensure that only one key influencing parameter is being investigated. Of the three evacuations undertaken, Trials 1 and 2 (100 BG slipform and 22 BG jumpform) involved formwork workers undertaking different tasks, i.e. dismantling or reshaping the slipform in Trial 1 and fixing rebar ahead of a scheduled concrete pour for Trial 2 while the ***top*** of the formworks were at similar heights: Level 21 for Trial 1 and Level 15 for Trial 2. While the level of construction in both cases is not identical, they are of a similar height. Furthermore, it has already been demonstrated (see Section 4.6.1.2) that, for workers undertaking similar tasks, height of construction is not an important factor in determining response time. So these two trials can be used to explore the impact of work type on response time.

Comparing the RT distributions for Trial 1 (see Figure 54 as measured from alarm 2) and Trial 2 (see Figure 59) we note that while the distributions look similar in nature (i.e. both normal distributions), the response times in Trial 2 are considerably longer than those in Trial 1 (see Figure 91). Table 20 shows the key distribution statistics for the two trials and clearly shows that the mean response time for Trial 2 is almost twice as large (92% larger) as that for Trial 1. The second test performed was comparing the combined jumpform RT distribution (i.e. Trials 2 and 4) to the slipform distribution from Trial 1. Note, that the nature of the works being undertaken in the formworks were very different, with the slipform being partially dismantled (Trial 1) compared to the rebar being installed in the jumpform during both Trial 2 and Trial 4. To determine how similar the two distributions are, the independent two tailed t-test was performed. The t-test returned a value of $p = 0.019$, suggesting that the two data-sets are derived from different distributions.

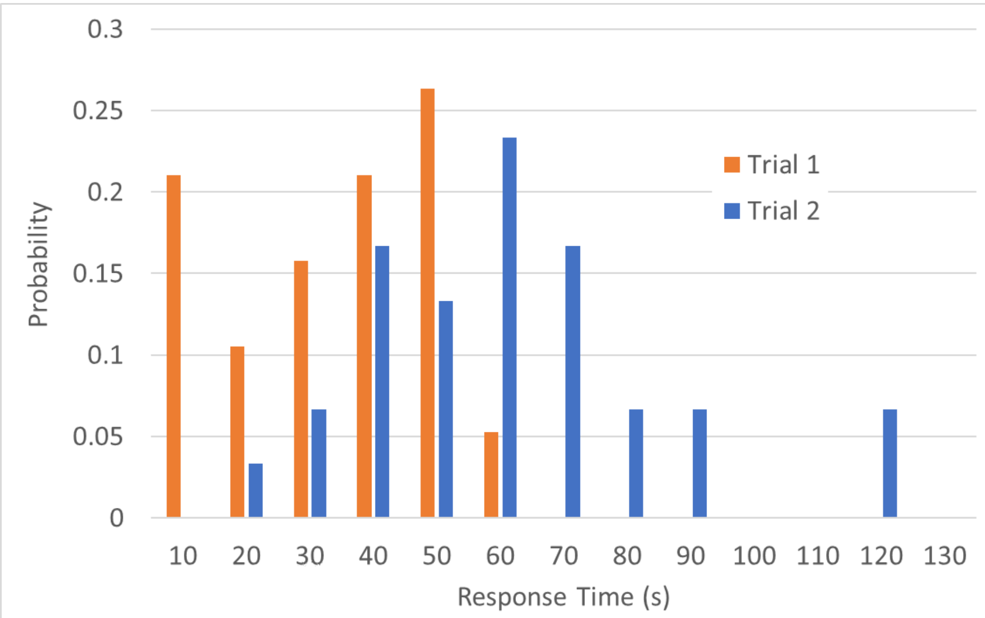


Figure 89. Comparison of formworks response times for Trial 1 and Trial 2.

Table 20. Summary of Trial 1 and Trial 2 formworks response times.

Trial	Min (s)	Max (s)	Mean (s)	Standard deviation	Number of workers	Height level*
Trial 1	0.2	50.7	28.9	16.4	19	21
Trial 2	12.2	114.7	55.6	32.6	30	15

*: Top of formworks.

These results support the suggestion that the nature of the work being conducted at the time of the alarm results in the different RT distributions. It also suggests that formwork workers engaged in high-priority work such as fixing rebar prior to a concrete pour are likely to exhibit long response times, while workers engaged in low-priority work such as dismantling the formworks are likely to exhibit short response times.

While Trial 1 and Trial 2 (and by implication Trial 4) may indicate either extremity of the likely range of response times for workers in the formworks, it is noted that workers actually engaged in concrete pours may exhibit even longer response times than those of Trial 2 (and Trial 4) and so the values produced here should not be considered the maximum response times for those in the formworks.

Key Finding 6.4: Impact of nature of work on formworks RT distribution – Independent evacuation trials from two high-rise construction sites with formworks at similar levels, involving similar numbers of workers, and in which the workers were engaged in different phases of construction work, produced significantly different response times. The differences in response time are attributed to the nature of the work engaged in at the time of the alarm. Those involved in low-priority work, such as dismantling the formworks following a concrete pour, are likely to exhibit much shorter response times compared to those involved in high-priority work, such as fitting rebar just prior to a concrete pour. Average response times for those involved in high-priority work may be twice as long as for those involved in low-priority work. Furthermore, as this work did not involve evacuating the formworks during a concrete pour – possibly the work with the highest priority – it is likely that even longer response times could be produced than those reported in this work.

4.6.1.4 Development of generalised response time probability distributions for the formworks

From Section 4.6.1.2 it is clear that the height of construction does not impact the RT distribution of workers in the formworks, while from Section 4.6.1.3 it is clear that the nature of the work has a significant impact on the RT distribution. It is also clear from this analysis that the nature of the RT distributions for workers in the formworks are normal rather than lognormal.

Given the data generated it is possible to produce generalised RT distributions that can be used to represent workers engaged in activities within the formworks of high-rise construction sites. The analysis suggests that two types of distribution are required: one representing the workforce when engaged in high-priority activities (see Section 4.6.1.2), which can be represented by the combined Trial 2 and Trial 4 distributions, and the other representing the workforce when engaged in low-priority activities (see Section 4.6.1.3), which can be represented by the Trial 1 distribution.

From the analysis in Section 4.6.1.2 the results of the t-test suggested that the data from the Trial 2 and Trial 4 distributions could be represented by a single distribution. This means that the two data-sets can be merged to form a single distribution (see Figure 90). The combined distribution has 60 data points (excluding the eight supervisors from both trials), with minimum, maximum and mean response time of 4.8 s, 133.2 s and 57.1 s (see Table 21). Visual inspection of the combined distribution suggests that this is also normal in appearance and this is confirmed by a Shapiro-Wilks test (p = 0.092).

The equation describing the generalised RT distribution for the formworks is presented in Equation 5.

$$\boldsymbol{f(t) = \frac{1}{28.554\sqrt{2\pi}} \exp\left[-\frac{(t - 57.08)^2}{2 * 28.554^2}\right]} \qquad \textbf{(5)}$$

Where t (response time) is between 0 and 133 s, the mean is 57.08 and the standard deviation is 28.55. This can be used for formworks located at up to Level 33 (34 levels).

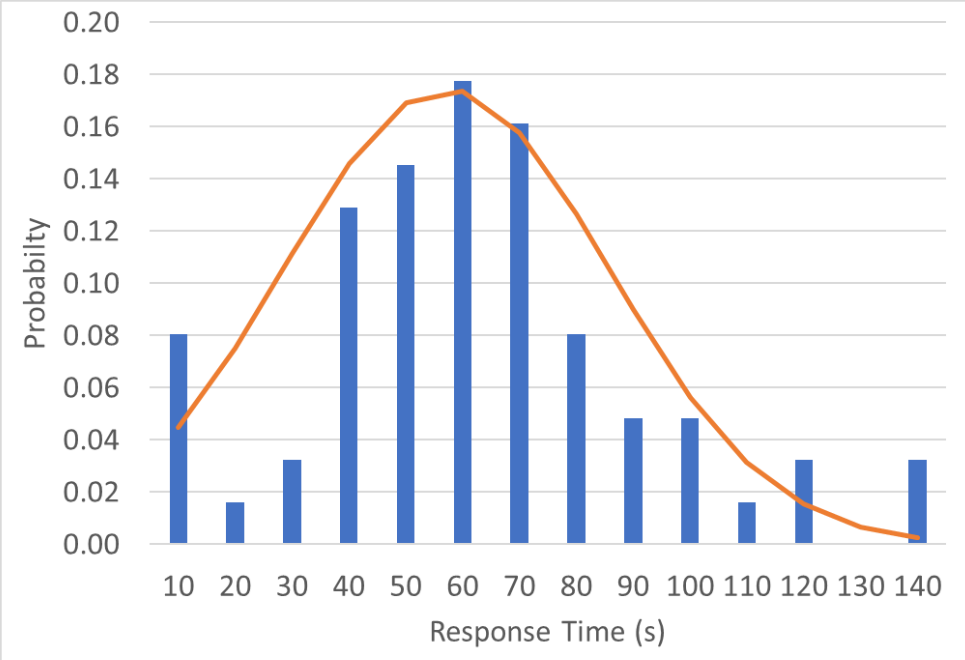


Figure 90. Combined (Trials 2 and 4) response time distribution for workers in the formwork engaged in high-priority work, excluding supervisors.

Equation 5 (and Figure 90) represents the generalised response time distribution for workers in the formwork engaged in high-priority work, e.g. fitting rebar prior to a concrete pour. This distribution can be used for formworks located at up to Level 33 and excludes the response times for supervisors. If the impact of supervisors is required within a simulation, it is suggested that the data from Table 19 can be used to represent the time at which supervisors are likely to disengage from their pre-alarm activity and engage in the role of alerting the other workers.

Equation 5 represents the suggested response time distribution to be used to represent workers engaged in high-priority activity within the formworks prior to a concrete pour, the so-called **HPFW (high-priority formworks) distribution.**

In contrast, the generalised response time distribution for those involved in low-priority activities, e.g. dismantling the formworks, can be described by the distribution for Trial 1 (see Section 4.6.1.3 and Figure 84). The Trial 1 response time distribution was fitted with a normal distribution using Microsoft Excel 365. The goodness of fit was determined using the Shapiro-Wilks test as measured by IBM SPSS 25. The equation describing the generalised response distribution for the low-priority work in the formworks is presented in Equation 6.

Equation 6 represents the suggested response time distribution to be used to represent workers engaged in low-priority activities within the formworks following a concrete pour, the so-called **LPFW (low-priority formworks) distribution.**

$$\boldsymbol{f(t) = \frac{1}{16.408\sqrt{2\pi}} \exp\left[-\frac{(t - 28.9)^2}{2 * 16.408^2}\right]} \qquad \textbf{(6)}$$

Where x (response time) is between 0 and 51 s, the mean is 28.9 s and the standard deviation is 16.4. This can be used for formworks located at up to Level 33 (34 levels).

A summary of the data used to define the two distributions is presented in Table 21.

Table 21. Summary of Trial 1 and Trial 2 formworks response times.

Data-set	Derived from	Min (s)	Max (s)	Mean (s)	Standard deviation	Number of workers
LPFW	Trial 1	0.2	50.7	28.9	16.4	19
HPFW	Trials 2 and 4*	4.8	133.2	57.1	28.6	60

*Excludes data from 8 supervisors, 2 from Trial 2 and 6 from Trial 4.

It is suggested when dealing with a regulatory required or general safety analysis that the HPFW response time distribution (Equation 5) is used to represent the RT distribution of the workers in the formworks. It is also important to note that response times may be longer than represented by the HPFW if the evacuation occurs during a concrete pour. Furthermore, if it is necessary to represent the response behaviour of supervisors within the formworks this can be represented using the data presented in Table 19.

Key Finding 6.5: Generalised RT distributions for the formworks – Two generalised response time distributions (HPFW and LPFW) have been defined to represent the response behaviour of workers in the formworks. The HPFW distribution, based on data from two trials and involving 60 data points, represents the response time distribution for workers involved in high-priority activities such as installing rebar prior to a concrete pour. It is recommended that this be used when dealing with a regulatory required or general safety analysis as it represents the longest response times observed. The LPFW distribution (based on 19 data points) can be used to explore the impact of an evacuation at other times during the construction phase. It is also important to note that response times may be longer than represented by the HPFW if the evacuation occurs during a work phase of extremely high priority such as a concrete pour.

4.6.2 Response time distributions for the main building (excluding formworks)

In this section the data from Trials 1, 3 and 4 will be considered as these are the only ones that involve workers located in the main building at the time of the alarm.

The analysis in this section will explore the RT distributions to establish the following:

- nature of the curve describing the response time probability distributions
    - does the RT distribution for the building follow the usual lognormal distribution or the normal distribution?
- impact of height on the response time probability distributions
    - does the height at which workers are located impact worker response time? If so, in what way?
- development of a generalised response time probability distributions
    - can we specify a generalised RT distribution for workers in the main part of the building? If so, how general are these relationships?

4.6.2.1 Nature of the curve describing the response time probability distributions

When analysing the RT distributions, it was noted that the general shape of these distributions for the building excluding the formworks (henceforward in this section this will be referred to simply as the main building) appeared to be lognormal (see Sections 4.1 to 4.3). Each RT distribution is also presented in Figure 91–93. As can be seen, in the main building, a considerable number of workers tend to respond to the alarm early with fewer workers responding with longer response times, resulting in the lognormal nature of the distribution.

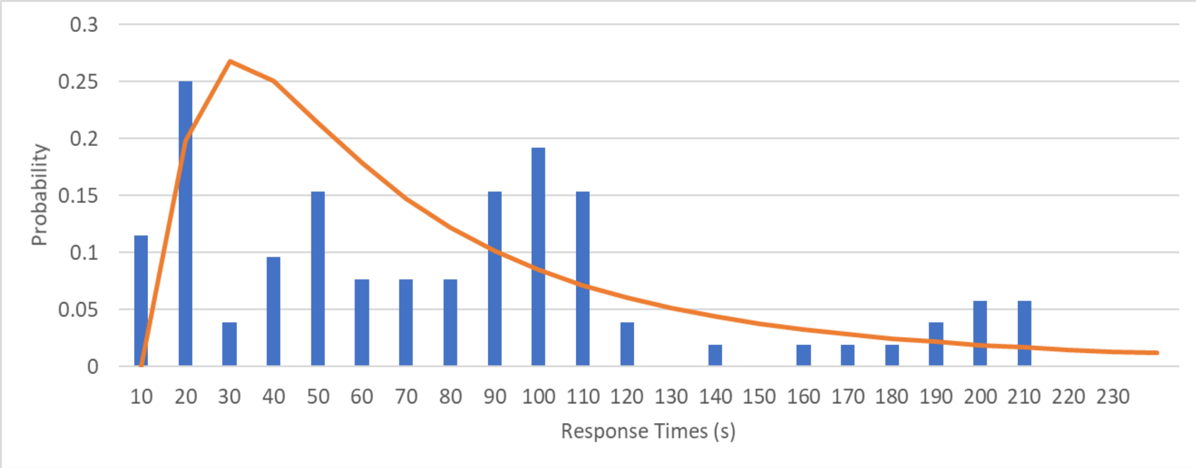


Figure 91. Response time distribution for Trial 1, excluding the jumpform workers.

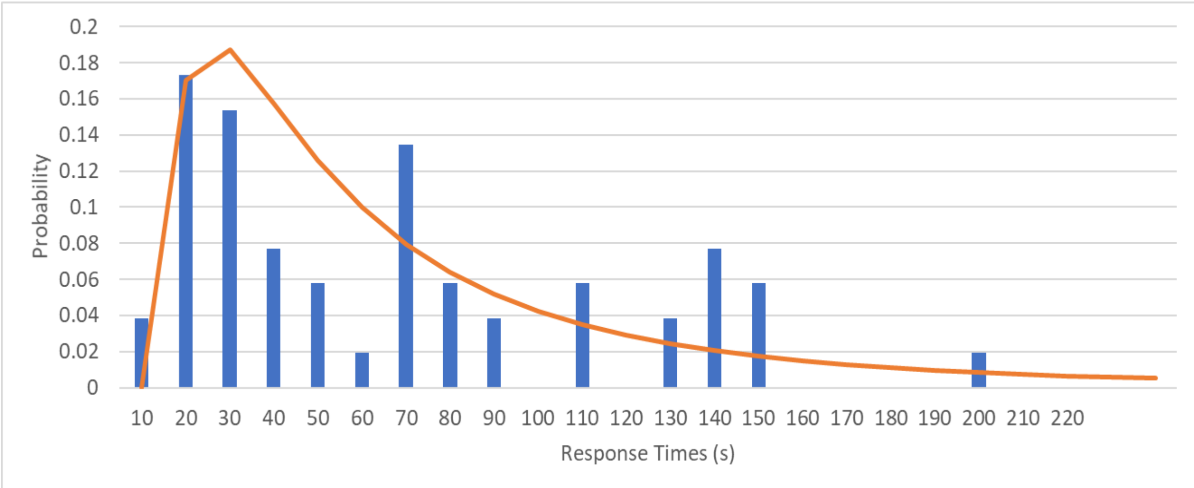


Figure 92. Response time distribution for Trial 3, excluding the jumpform workers.

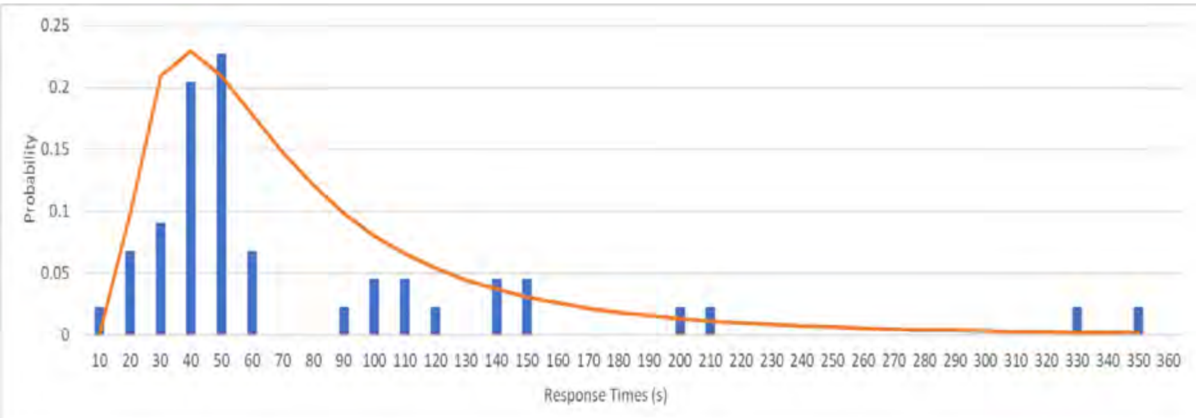


Figure 93. Response time distribution for Trial 4, excluding the jumpform workers.

For each of the three data-sets, the distributions were fitted with a lognormal distribution using Microsoft Excel 365. The fitted curves for each distribution are described by Equations 7 to 9 along with the goodness of fit.

$$f(t) = \frac{1}{0.958t\sqrt{2\pi}} \exp\left[-\frac{(ln(t) - 3.96)^2}{2 * 0.958^2}\right] \quad (7)$$

Where 8.8 < t (response time) < 204. The mean is 3.96 and the standard deviation is 0.958.

$$f(t) = \frac{1}{0.988t\sqrt{2\pi}} \exp\left[-\frac{(ln(t) - 3.76)^2}{2 * 0.988^2}\right] \quad (8)$$

Where 0.88 < t < 191. The mean is 3.76 and the standard deviation is 0.988.

$$f(t) = \frac{1}{0.796t\sqrt{2\pi}} \exp\left[-\frac{(ln(t) - 3.98)^2}{2 * 0.796^2}\right] \quad (9)$$

Where 9 < t < 340. The mean is 3.96 and the standard deviation is 0.958.

Finding 6.1: Main building RT distributions – The response times for workers throughout the building, excluding the formworks, can be represented using a lognormal distribution. This is the typical distribution used to describe most response time distributions, but it is different to the response distribution used to describe workers in the formworks, which is normal in nature. The lognormal relationship has been observed for three different unannounced full-scale evacuation trials conducted in two different buildings.

4.6.2.2 Impact of height on the response time probability distributions for workers in the main building

Unlike in the formworks, where predominately one type of work is undertaken at any one time, throughout the main building workers are always engaged in a variety of different jobs. Hence it is not practical to specify one predominate type of work when describing the main building response time, and so work type is not a key parameter controlling the response time distribution for the main building. Also, when considering the workers in the formworks, all the workers are essentially located at the same level of the building, i.e. the upper two levels. Thus for workers within the formworks it is straightforward to specify the level at which they are located and hence explore the impact of height on response time distribution. For workers in the main building this is more challenging as they can be located throughout the building, from the lowest level to the highest levels. Simply restricting the comparative analysis to those workers located at the highest levels could result in an unrepresentative analysis as this would not only restrict the number of data points in the analysis, it may also limit the types of work involved.

It is therefore essential to know the floor distribution for those workers in the main building for which response times have been determined. This information is presented in Table 22. From this data we note that Trial 1 and Trial 4 have similar worker distributions, with Trial 1 having 58% of workers located below Level 10 and 42% of workers located between Level 11 and Level 15, while Trial 4 has 82% of workers located below Level 7 and 18% of workers located between Level 18 and Level 19. In both cases the majority of workers are located on the lower levels (less than Level 10), with the remainder located no higher than Level 19. Trial 3, however, has a significantly different worker distribution. In this case, the majority of workers are located above Level 22 (56%) with 42% of workers located between Level 33 and Level 38.

Table 22. Distribution of workers in the main part of the building (excluding ground floor) for which response times were measured.

Level	Trial 1 100 BG			Trial 3 100 BG			Trial 4 22 BG		
	#	%	Cum %	#	%	Cum %	#	%	Cum%
1–3	15	25.0	25.0	0	0	0	0	0	0
4–5	0	0	25.0	0	0	0	35	79.5	79.5
6	7	11.7	36.7	21	40.4	40.4	1	2.2	81.7
7–9	13	21.7	58.4	0	0	40.4	0	0	81.7
10	0	0	58.4	2	3.8	44.2	0	0	81.7
11–15	25	41.6	100.0	0	0	44.2	0	0	81.7
18–19	-	-	-	0	0	44.2	8	18.2	100
22–23	-	-	-	5	9.6	53.8	-	-	-
27	-	-	-	2	3.8	57.6	-	-	-
33–38	-	-	-	22	42.3	100.0	-	-	-
Formwork	20			-			43		

Thus, comparing the RT distribution from Trial 1 with Trial 3 and the RT distribution from Trial 4 with Trial 3, this should provide insight into whether or not height exerts a strong influence on worker RT distribution within the main building. To determine whether height influences the RT distribution for workers in the main building the independent two tailed t-test was used again to assess whether any given two response time data-sets could be defined by the same distribution. However, the two tailed t-test is strictly only valid for distributions with normality. To address this issue, each data point (individual response time) was transformed using the Ln(x) function before the t-test was calculated. Once again, if the p-value returned from the t-test is greater than 0.05 then it is likely that the two data-sets can be said to be derived from the same distribution.

Comparing Trial 1 (majority of workers located on the lower levels) to Trial 3 (majority of workers located on higher levels) the t-test returned a p-value of 0.64, and therefore the two data-sets can be said to be derived from the same distribution. This suggests that height of construction does not impact the RT distribution for the main building. However, both data-sets come from the same building site i.e. 100 BG, albeit at very different times, Trial 1 in February 2017 and Trial 3 in October 2017.

Comparing Trial 4 (majority of workers located on the lower levels) to Trial 3 (majority of workers located on higher levels), the t-test returned a p-value of 0.297, and therefore the two data-sets can be said to be derived from the same distribution. This again suggests that height of construction does not impact the RT distribution for the main building. Furthermore, the data-sets are derived from two different building sites at two different times (Trial 4 22 BG November 2017 and Trial 3 100 BG October 2017).

This is an important observation as it suggests that for construction sites up to 39 levels high (ground is Level 0), the response time of workers in the main building and the formworks are not impacted by the height of the construction. As noted for the workers in the formworks, this result may be due to the workers' perception that they are not at risk while on the construction site (see Section 4.5.7).

Key Finding 6.6: Impact of height on main building RT distribution – Three independent evacuation trials from two high-rise construction sites, two with the majority of workers located below Level 10 and one with the majority of workers located between Levels 33 and 38, suggest that the response time distribution is not impacted by height. This suggests that for high-rise construction sites up to 39 levels, the response times for workers are not impacted by height of construction. This

observation may be the result of construction workers not perceiving that they are at risk while on the construction site.

4.6.2.3 Development of generalised response time probability distribution for the main building

From Section 4.6.2.2 it is clear that the height of construction does not impact the response time distribution of workers in the main building. It is also clear from this analysis that the nature of the response time distributions for workers in the main building are lognormal in appearance (see Section 4.6.2.1). Given the data generated, it is possible to produce generalised response time distributions that can be used to represent workers engaged in activities throughout the main building of high-rise construction sites.

From the analysis in Section 4.6.2.2 the results of the t-test suggested that the data from Trial 1 and Trial 3 could be represented by a single distribution and that the data from Trial 4 and Trial 3 could be represented by a single distribution. The t-test can also be applied to the data-sets from Trial 1 and Trial 4 to determine if these can be represented by a single distribution.

Comparing Trial 1 (majority of workers located on the low floors) to Trial 4 (majority of workers located on low floors) the t-test returned a p-value of 0.38, and therefore the two data-sets can be said to be derived from the same distribution.

These results suggest that all three data-sets are likely to be derived from the same distribution and so can be combined to form a generalised response time distribution. Presented in Table 23 is a summary of the key response time data describing each distribution and the combined distribution.

Table 23. Summary of main building (above ground level) response time data for the three unannounced high-rise construction site evacuations.

Trial and date	Number of floors	Number of data points	Min (s)	Max (s)	Average (s)	Standard deviation
Trial 1 100 BG Feb 17	19 core 12 floors	60	8.8	203.8	76.4	56.9
Trial 3 100 BG Oct 17	38 core 33 floors	53	0.9	191.2	61.6	47.1
Trial 4 22 BG Nov 17	32 core 20 floors	44	9.0	340.2	75.3	73.1
Combined data-set		157	0.9	340.2	71.5	58.1

As in Section 4.6.2.1, the combined distribution was fitted with a lognormal distribution using Microsoft Excel 365. The fitted curve for the combined distribution is described by Equation 10 along with the goodness of fit and the combined data curve is presented in Figure 94.

$$\boldsymbol{f(t) = \frac{1}{t0.938\sqrt{2\pi}} \exp\left[-\frac{(\ln t - 3.908)^2}{2 * 0.938^2}\right]} \qquad \textbf{(10)}$$

Where t (response time) is between 0 and 340 s, the mean is 3.9 (71.5 s) and the standard deviation is 0.9. This response time distribution has been labelled the **Main Building (MB)** response time distribution and can be used for main buildings up to Level 38 (39 levels).

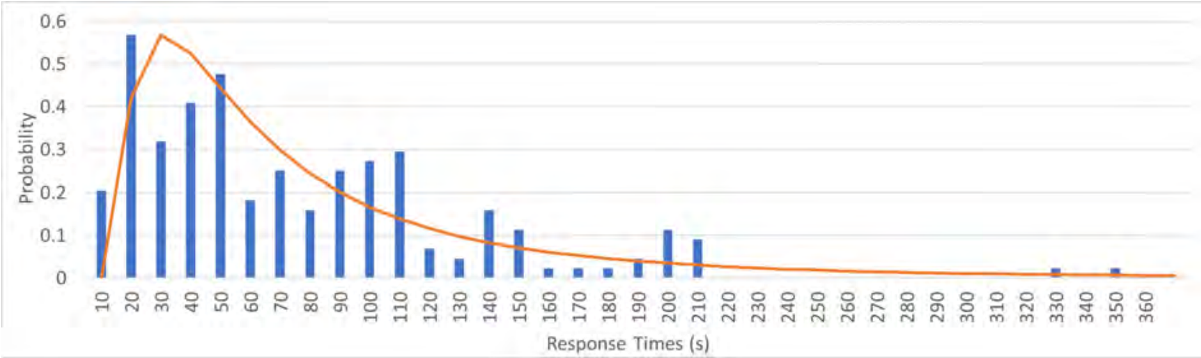


Figure 94. Combined response time distribution (Trials 1, 3 and 4) for workers in the main building (excluding the formworks).

Equation 10 (and Figure 94) represents the generalised response time distribution for workers in the main building engaged in a variety of activities including rebar fitting, glazing, MEP, etc. and includes those working at height and isolated workers. It is suggested when dealing with a regulatory required or general safety analysis that the MB response time distribution (Equation 10) is used to represent the response time distribution of the workers in the main building. However, while the data-set includes 157 data points from three unannounced trials in two different buildings, it cannot be considered as a definitive data-set as workers involved in pouring concrete and workers in high tower cranes are not included. It is suggested that these workers are likely to contribute to the tail of the response time distribution, possibly extending the tail to longer response times or increasing the frequency of those workers with longer response times. Furthermore, the data was collected for heights of construction up to Level 38 (39 levels), so it cannot be used with a great deal of confidence for higher construction.

Key Finding 6.7: Generalised RT distribution for the main building – A generalised response time distribution has been defined to represent the response behaviour of workers in the main building (MB). The MB distribution, based on data from three trials in two buildings involving 157 data points, represents the response time distribution for workers involved in a variety of activities such as fitting rebar, glazing, MEP, etc., and includes those working at height and isolated workers within heights of construction up to Level 38 (39 levels). It is also important to note that the MB data-set does not include workers involved in concrete pours or workers in high tower cranes. It is suggested that these workers are likely to contribute to the tail of the response time distribution, possibly extending the tail to longer response times or increasing the frequency of those workers with longer response times.

4.6.3 Disengagement time and number of tasks undertaken during response phase

In this section the data from Trials 1, 3 and 4 relating to the time to disengage from the pre-alarm activities and the number of tasks undertaken during the response phase are presented. As described in Section 2.1.1 the time to disengage from the pre-alarm activities and begin to engage in the activity phase represents a key time in the evacuation process. The sooner that the individual disengages from their pre-alarm activities, the sooner they can confirm the need to evacuate (by performing information tasks), and if required, prepare to start the evacuation movement phase (by performing action tasks). The duration of the response phase is then made up of the time to disengage from the pre-alarm activities and the time required to undertake the various tasks perceived to be necessary before physical movement to exit the building can begin. Generally, the more tasks undertaken the longer the duration of the activity phase, and hence the longer the response time. Ideally, individuals disengage rapidly and undertake as few information and action tasks as possible.

Presented in Figure 95 is the probability distribution for the time required to disengage from the pre-alarm activities and engage in the activity phase, while in Figure 96 is the probability distribution for the number of tasks undertaken by the population for Trials 1, 3 and 4 combined. It is noted that it was not possible to determine the time nor the corresponding number of tasks undertaken during the activity phase for the occupants in the formworks (hence there is no data from Trial 2).

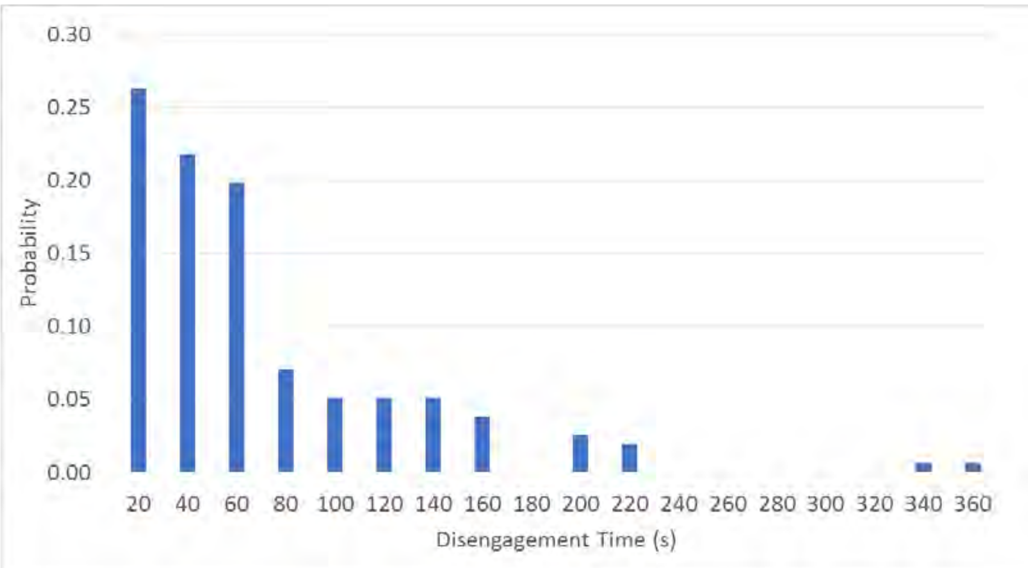


Figure 95. Time to disengage from pre-alarm activities and start activity phase for Trials 1, 3 and 4.

In Trials 1, 3 and 4 it was possible to determine the time to disengage and the number of tasks undertaken during the activity phase for a total of 156 individuals, while for Trial 1 this was possible for 60 individuals.

From Figure 95, 48% (75) of the total population disengage from pre-alarm activities in less than 40 s. This suggests that almost half the population across the trials took the alarm seriously and rapidly disengaged from their pre-alarm activities (48% (29) in Trial 1). However, more than 50% of the population took longer than 40 s to disengage from their pre-alarm activities with almost one-third (32% or 50) of the total population requiring more than 60 s to disengage.

Once disengaged, the number of tasks (action and information combined) most frequently undertaken by the entire population is 0 – undertaken by 29% (45) of the population – while 41% (64) of the population undertook at most one task (see Figure 96). This suggests that 41% of the entire population started to evacuate almost immediately after they disengaged (for Trial 1 this equates to 32% (19)).

Key Finding 6.8: For Trials 1, 3 and 4, 48% of the total population (excluding the formworks) rapidly disengage from their pre-alarm activities on hearing the alarm, i.e. in less than 40 s (48% in Trial 1), with 41% of the population undertaking at most only one task before they start to evacuate (32% in Trial 1). This suggests that a significant proportion of the population react to the alarm in an appropriate manner, rapidly disengaging and starting their evacuation movement phase without undertaking many preparation activities.

Nevertheless, almost a third (32%) of the total population require more than 60 s to disengage from their pre-alarm activities and once disengaged the population as a whole undertake an average of 2.2 tasks (2.5 for Trial 1), with almost a quarter (23%) of the population undertaking four or more tasks. The long time to disengage and the large number of tasks undertaken explains some of the long response times noted in the trials.

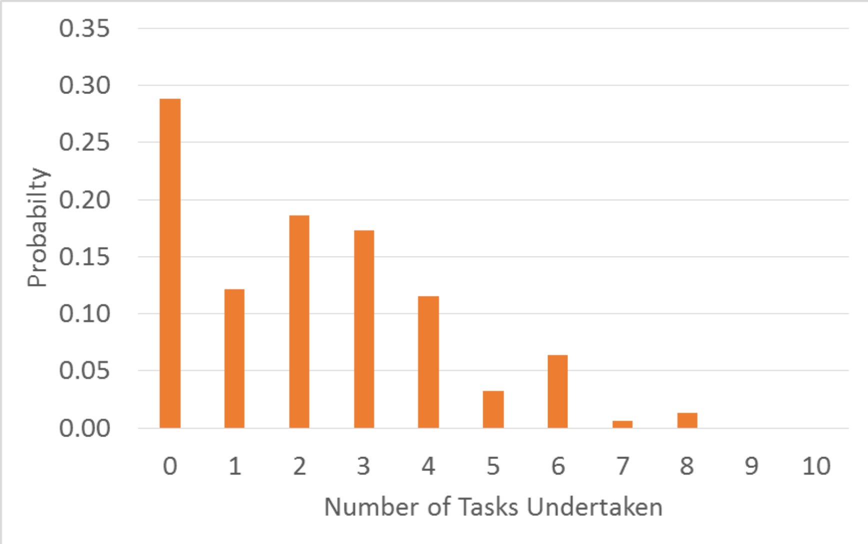


Figure 96. Number of tasks undertaken by individuals during the activity phase for Trials 1, 3 and 4.

4.7 Combined temporary stair usage data

In this section we present the combined results from the stair usage data. Only data from Trial 2 (see Section 4.2.4) and Trial 4 (see Section 4.4.4) was available and this was only for the temporary scaffold dogleg stair. In both cases it was the same staircase and the same flight of stairs. In Trial 2, the staircase ended on the ground floor, whereas in Trial 4 the staircase ended on Level 8.

The flight of temporary stairs consisted of nine treads and 10 risers. The depth of the tread was 0.189 m and the riser height was 0.202 m (47° angle) (see Figure 97). A standard stair has a typical tread depth of 0.202 m and a typical riser height of 0.196 m (36° angle). As a result, the temporary stair is steeper than the standard stair and the centre of two adjacent treads are spaced closer together horizontally than on a standard stair.

Figure 97. Tread and riser dimensions for the temporary scaffold dogleg stairs used in Trials 2 and 4.

The combined data from Trials 2 and 4 consists of 224 interpersonal spacing measurements from 130 workers from a total of 42 groups of workers. As identified in Section 3.8, a group is defined as a continuous collection of people who, when on the flight, are separated by fewer than five treads. The mean duration of the sampling interval between successive measuring events within a group was 1.1 s (see Table 24).

The data for both trials can be found in Appendix 4 and the key information for the combined data-set is presented in Table 24. The spacing frequency for the combined data-set is presented in Figure 97 while the frequency distribution for the number of people on the flight is presented in Figure 98.

Table 24. Summary of interpersonal spacing on stair flight for Trials 2 and 4 combined.

Parameter	Data
Minimum sampling period for a group	2.0 s
Maximum sampling period for a group	11.8 s
Mean sampling period for a group	4.6 s
Mean duration of a sampling interval between sampling events	1.1 s
Number of groups observed	42
Minimum group size	2
Maximum group size	8
Mean group size	3.1
Number of individual workers observed	130
Number of individual spacing measurements	224
Minimum spacing observed	1
Maximum spacing observed	6
Mean spacing observed	2.5
Minimum number of workers on stair flight	1
Maximum number of workers on stair flight	4
Mean number of workers on stair flight	2.1

Combining the data concerning occupant spacing and maximum occupancy from Trials 2 and 4 results in the frequency distributions presented in Figure 98 and Figure 99. From Figure 98 it can be seen that the modal stair spacing is 2 (101 occurrences representing 45% of the data), with the next most common stair spacing being 3 (65 occurrences representing 29% of the data). Presented in Figure 99 is a frequency distribution for the number of people on the flight. As can be seen, the modal number of people to occupy the flight is 2 (100 occurrences representing 49% of the data), with the next most common occupancy being 3 (59 occurrences representing 29% of the data), with a mean occupancy of 2.1. The maximum number observed on the flight is 4, with just 2 occurrences representing 1% of the data.

From these diagrams it can be seen that most frequent (modal) stair spacing is 2 with a mean stair spacing of 2.5. Similarly, the most frequent number of people (modal) to occupy a single flight is 2, with a mean occupancy of 2.1.

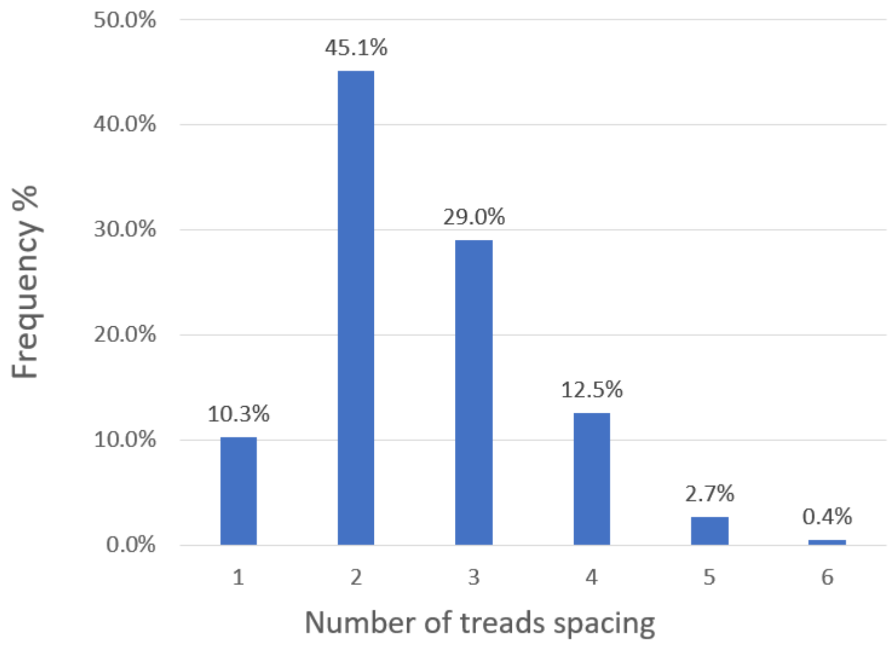


Figure 98. Occupant spacing on flight for Trials 2 and 4.

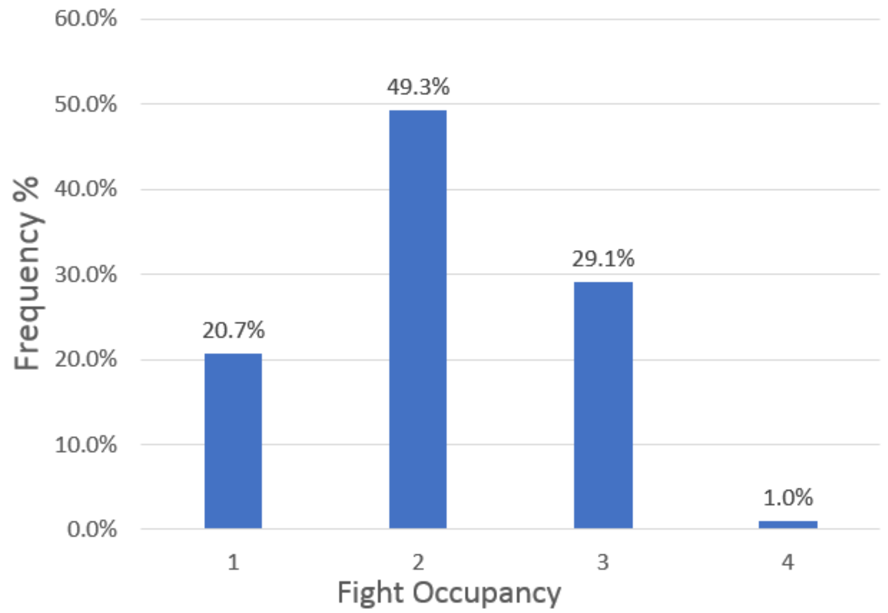


Figure 99. Flight occupancy for Trials 2 and 4.

However, as in Trial 4, the combined data-set provides sufficient data to undertake a more detailed analysis. In Figure 100 we present the frequency distribution for the interpersonal spacing when there are at least three people on the flight. As already noted, with more than two people on the flight the available space between occupants is more constrained and so provides a better representation of the likely minimum preferred spacing distance between stair occupants. We note that while occupants can get down to a spacing of 1 tread (20 occurrences representing 16% of the data), this represents a very low proportion of the observed interpersonal spacing distances. The modal interpersonal distance is 2 treads (65 occurrences representing 52% of the data) while the next most common spacing is 3 treads, but this represents only 22% (27 occurrences) of the observed spacings.

As noted in the analysis of the Trial 2 data, when based on the entire data-set (for the combined Trial 2 and Trial 4) the flight occupancy analysis is biased by the high number of small groups present in the data. If we restrict the analysis to groups with 3 or more workers, we have a better representation of the most likely maximum occupancy for the flight (see Figure 101). Using this approach, the most common number of people to occupy the flight is 3 (59 occurrences representing 46% of the data) with the next most common occupancy being 2 (50 occurrences representing 39% of the data). While 4 people have occupied the flight at one time, this only represents 2% (2) of the cases and so is a low likelihood event. Thus, for groups with three or more people, the most common maximum occupancy for the stair flight is 3.

From the Trial 2 and Trial 4 combined data-set, the minimum preferred spacing is 2 treads in situations where there are a 3 or more people attempting to occupy a flight simultaneously, and the maximum likely occupancy of the flight is 3.

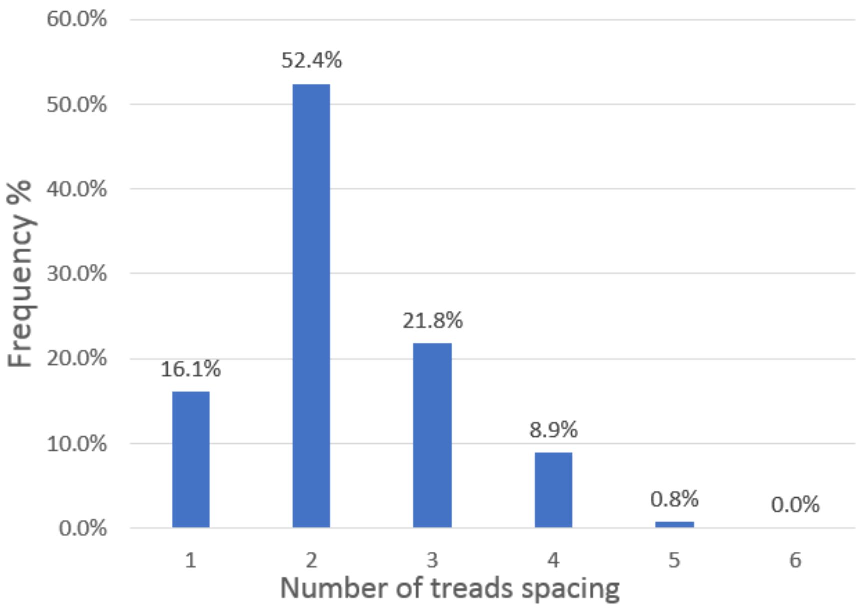


Figure 100. Occupant spacing on flight when three or more workers occupy the flight for Trials 2 and 4.

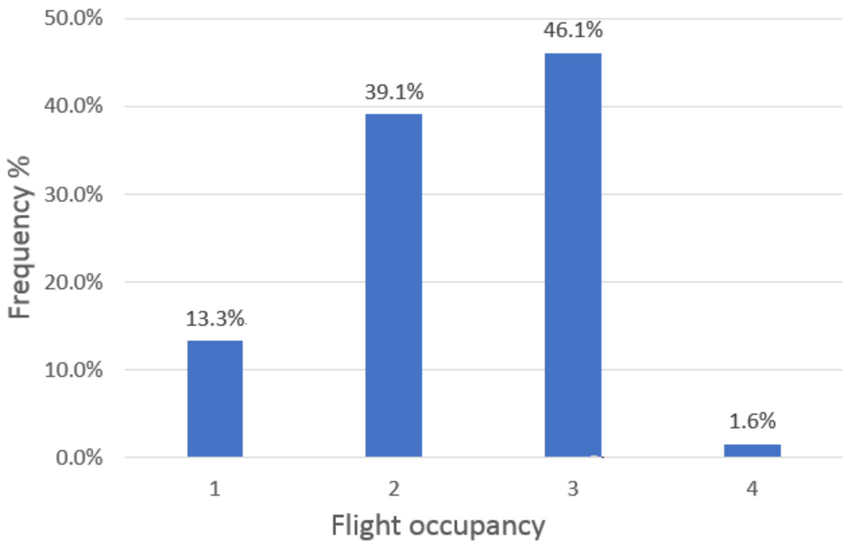


Figure 101. Flight occupancy for groups with three or more workers in Trials 2 and 4.

The data suggests that a maximum of 3 people is most likely to occupy a flight of temporary scaffold dogleg stairs at any one time, with the most frequent gap size of 2 unoccupied treads between them. On regular stairs (of the same width), a flight consisting of 9 treads (10 risers) would have a maximum occupancy of 5 people if walkers kept a single tread spacing between them – which is typically the case on congested normal stairs. There are several possible reasons why the occupancy on the temporary stairs is less than what is normally the case in standard permanent stairs. First, as already noted, on the temporary stair the horizontal spacing between the centre of adjacent treads is less than that for normal stairs. Thus, to maintain the same horizontal separation, occupants on the temporary stair would need to maintain a greater number of treads between them. As the temporary stair is also steeper than the regular stair, this also gives the impression that adjacent occupants are closer together than on less steep stairs. Finally, it is possible that due to the perception that the temporary stairs may not be as robust as a permanent stair that workers do not pack as densely (or closely) as they do on regular stairs, in order to reduce the number of people on a single flight. Furthermore, it may simply be due to insufficient data being collected given that only a single flight was observed on two stairs with a total of 224 data points collected from 130 stair users.

Nevertheless, this is an important observation as it suggests that temporary dogleg stairs are unlikely to carry as many people as a regular stair of the same width and covering a similar vertical drop. While attempting to maintain a 2-tread gap, this reduces the number of workers on a flight, decreasing the density of workers on a flight, and potentially constrains the speed at which workers may move on the flight. This in turn will have a negative impact on the flow achieved by the temporary dogleg stair, effectively reducing the flow, which in turn increases the time required to clear the section of the building served by the temporary stairs, compared to the situation where a regular stair was used. This observation is also significant for evacuation models which specify the minimum likely spacing of agents on the temporary scaffold stairs.

Key Finding 7.1: Behaviour on temporary stairs – A single flight of a single-lane temporary scaffold dogleg stair, with nine treads per flight, was monitored during two evacuation trials. The most frequently observed spacing between the occupants when three or more occupy the flight was two treads, and the most common number of people that was accommodated on the flight was three for groups consisting of three or more people. The observed spacing is significantly different to that found on regular building stairs, which is typically one tread between occupants in high-density situations. The cause of this apparent reluctance of users of temporary stairs to pack more densely is not clear. It may simply be a result of the smaller tread depth found on the temporary stair or it may also be due to the perceived fragility of the stair. The lower interpersonal spacing on the temporary stair will have a negative impact on the flow capability of the stair, essentially decreasing the flow compared to a permanent stair of similar width. While these observations are based on measuring the behaviour of a large number of people (130) it is possible that the conclusions could be a result of the size of the data-set or the number of people attempting to use the monitored stair at any one time.

4.8 Walking speed experiments

In this section we present the results from the walking speed experiments. Data will be presented describing horizontal walking speeds over four different types of surface and vertical speeds on two different types of stairs. In total 152 workers participated in the five experiments, generating a total of 671 data points (see Table 25). More than 100 data points were collected for each of the four floor types. In total 126 data points were collected for walking speeds on stairs; however, this was made up of 73 data points for the dogleg stairs and 53 data points for the parallel stairs. It is noted that in some experiments at least one worker walked out of the trial before completion, while in some experiments, the workers failed to complete a leg correctly, i.e. stopped before reaching the end point.

Table 25. Summary of data collected from the walking speed trials.

Trial	Building	Date	Number of participants	Data points collected	Concrete	Across decking	Rebar	Along decking	Dogleg stairs	Parallel stairs
1	100 BG	Feb-17	29	131	27	28	27	28	n/a	21
2	100 BG	May-17	30	114	29	28	-	28	29	n/a
3	22 BG	Sep-17	28	124	26	25	27	25	21	n/a
4	100 BG	Oct-17	42	187	39	38	39	39	n/a	32
5	22 BG	Dec-17	23	115	23	23	23	23	23	n/a
Total			152	671	144	142	116	143	73	53

4.8.1 Horizontal walking speeds across concrete, metal decking and rebar floor surfaces

There are three different types of surfaces that workers could be required to walk over during an evacuation from a construction site. These surfaces consist of concrete (see Figure 40a), metal decking with rebar (see Figure 40b) and metal decking (see Figure 40c). Furthermore, unlike other surface types, when walking over the metal decking, the direction of travel has an impact on walking speed, in particular walking along the direction of the decking ridges is more difficult (i.e. slower) than walking perpendicular to the ridges (see Figure 40c).

Presented in Figure 102 to Figure 105 are the distributions of walking speed data extracted from the experiments for each of the surfaces: concrete (Figure 102), across decking (Figure 103), rebar (Figure 104) and along decking (Figure 105). Visually, each distribution appears to be normal and the Shapiro-Wilks test confirms this. The figures are arranged from fastest average speed to slowest average speed. Presented in Table 26 is a summary of the key data from these trials.

From the average speeds for each surface type (see Table 26), we note that the speed across concrete is the fastest, followed by the walking speeds across metal decking, then rebar and then the walking speeds along metal decking. The nature of this data suggests that there could be a relationship between travel speed and the type of floor surface.

Finding 8.1: Walking speeds on different surfaces – Walking speeds are impacted by the type of surface and are on average greatest on concrete, followed by across metal decking and on rebar, while the slowest average speeds were measured for along decking.

It is also noted from the distributions and the average walking speed data presented in Table 26 that over all four surface types the speeds are quite high, with the average speed over the concrete surface being 1.9 m/s. While all participants were instructed NOT to run it was clear from observations that many participants were walking very fast, if not virtually breaking into a run. The speeds on concrete exceed normal walking speeds which are typically around 1.2 m/s to 1.5 m/s. The high speeds were a combination of the relatively short distances that the workers had to walk over, i.e. approximately 18 m, and also their desire to complete the experiments as quickly as possible so they could resume work.

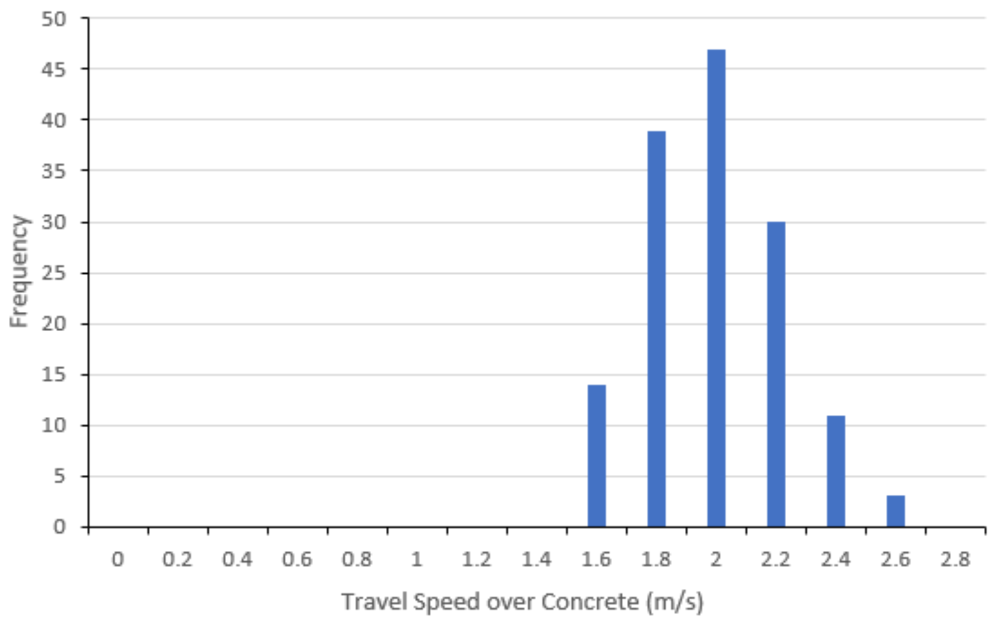


Figure 102. Summary of walking speed trial data for the concrete surface.

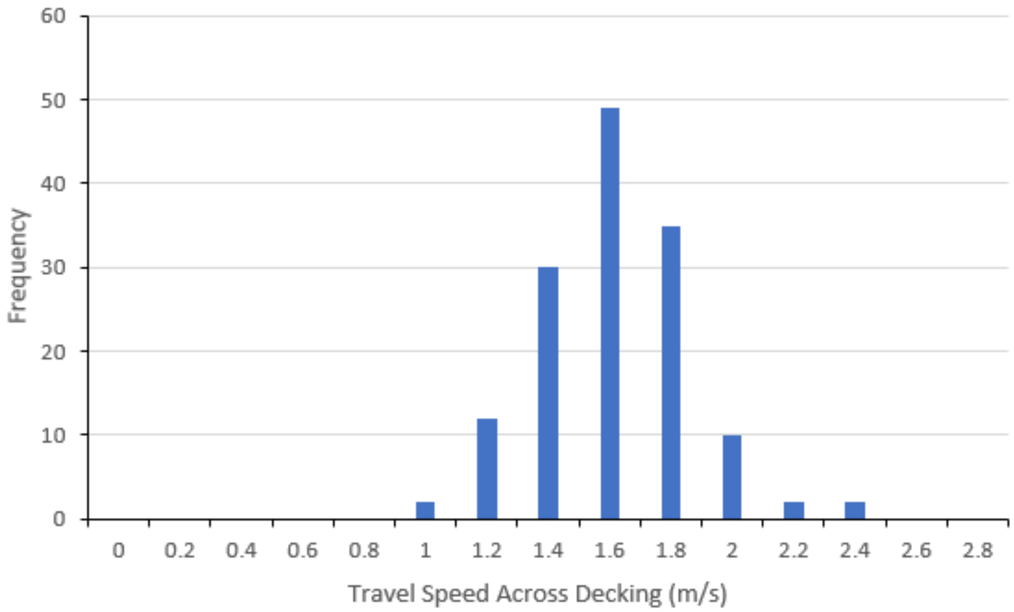


Figure 103. Summary of walking speed trial data for the across decking surface.

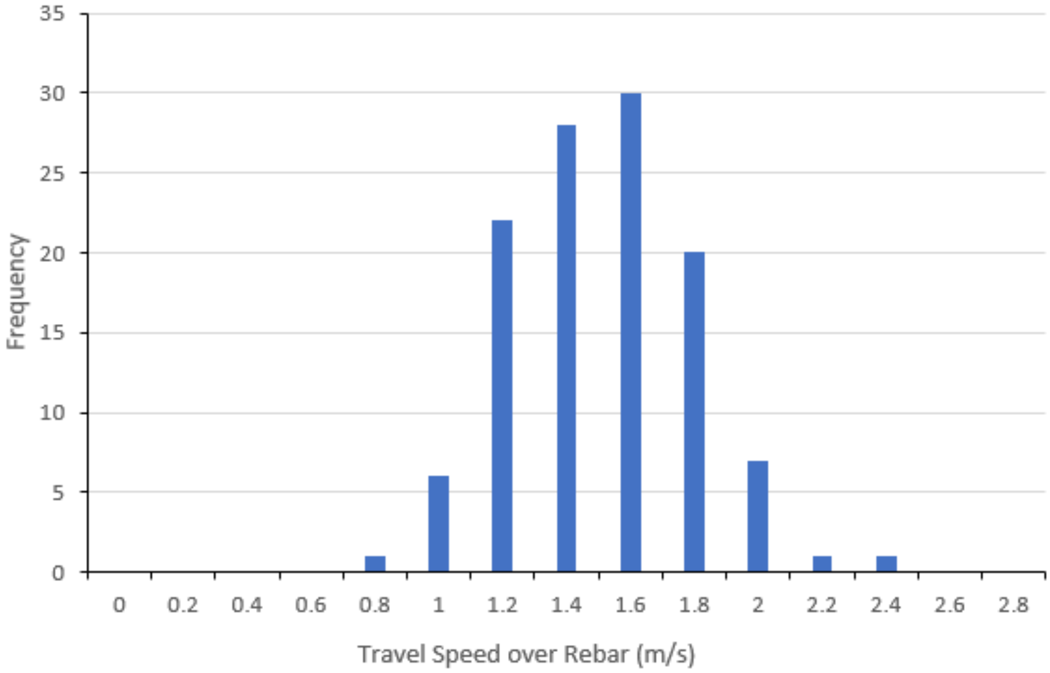


Figure 104. Summary of walking speed trial data for the rebar surface.

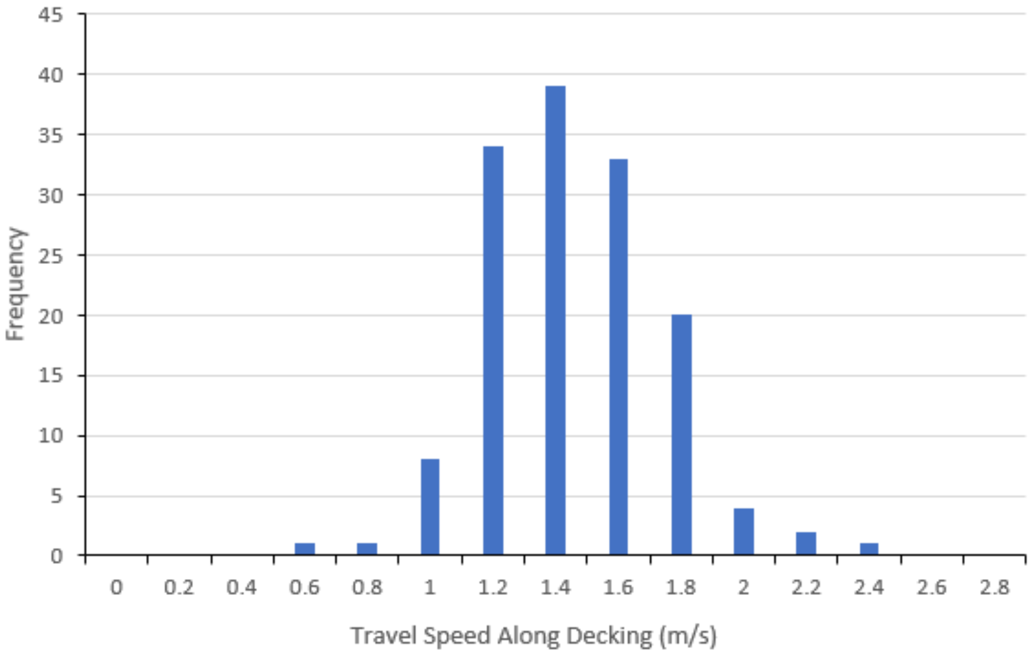


Figure 105. Summary of walking speed trial data for the along decking surface.

Table 26. Walking speed data for the four types of surface.

Surface type	Min (m/s)	Max (m/s)	Average (m/s)	Standard deviation	# data points
Concrete	1.43	2.52	1.89	0.23	144
Across decking	0.93	2.25	1.50	0.24	142
Rebar	0.64	2.29	1.41	0.29	116
Along decking	0.45	2.23	1.36	0.27	143

In addition to the walking speeds over the various surfaces, a relationship between a person's speed over the concrete surface (normal surface) and the other surface types was investigated. In this case the speed of each participant over concrete is compared with their speed over the other surface types. In this way it is hoped that a global reduction factor for each surface type can be determined. The comparative graphs are presented in Figure 106–108 including the line of best fit (passing through the origin) and the correlation values (R^2).

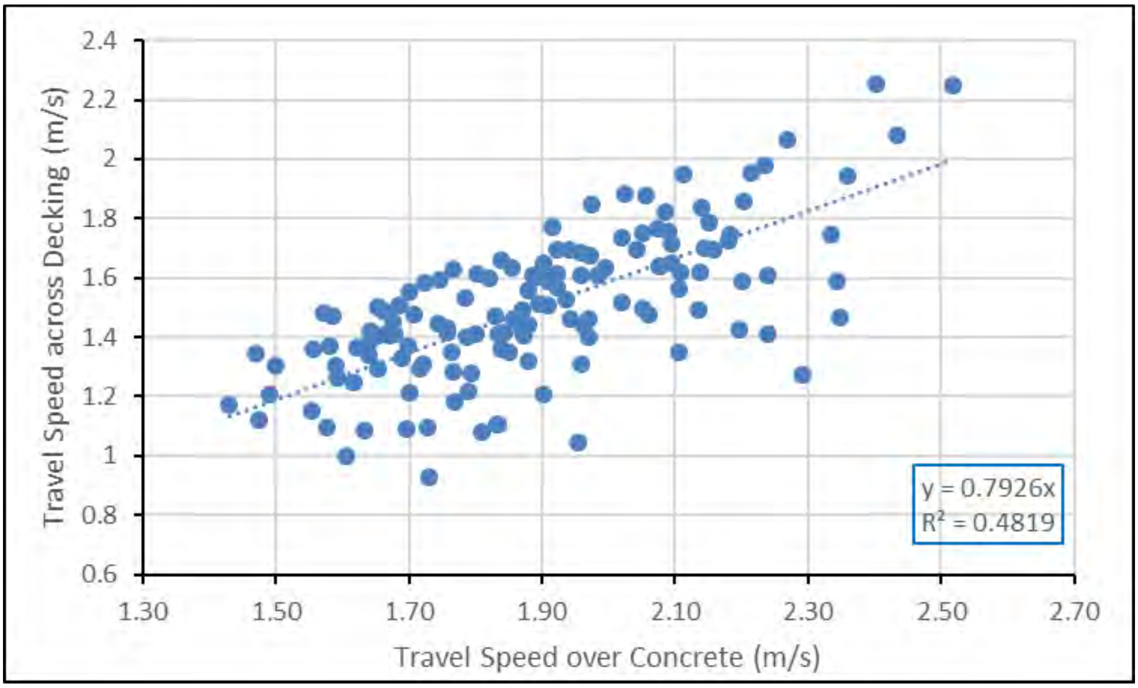


Figure 106. Comparison of individual walking speed across metal decking with walking speed on concrete.

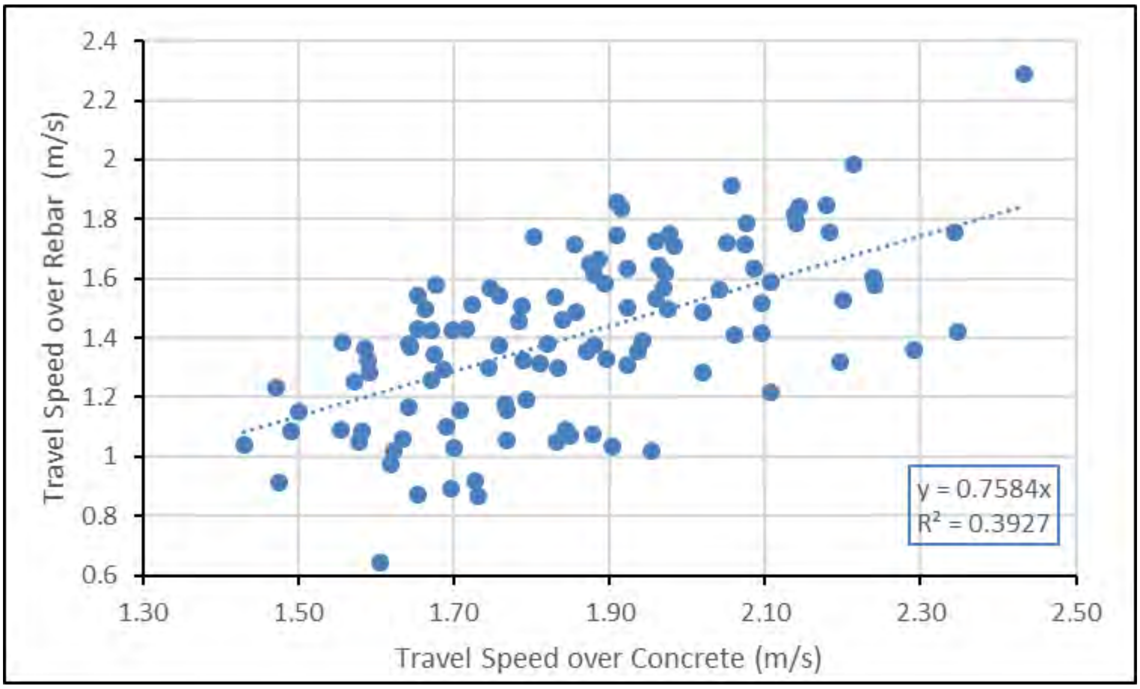


Figure 107. Comparison of individual walking speed on rebar with walking speed on concrete.

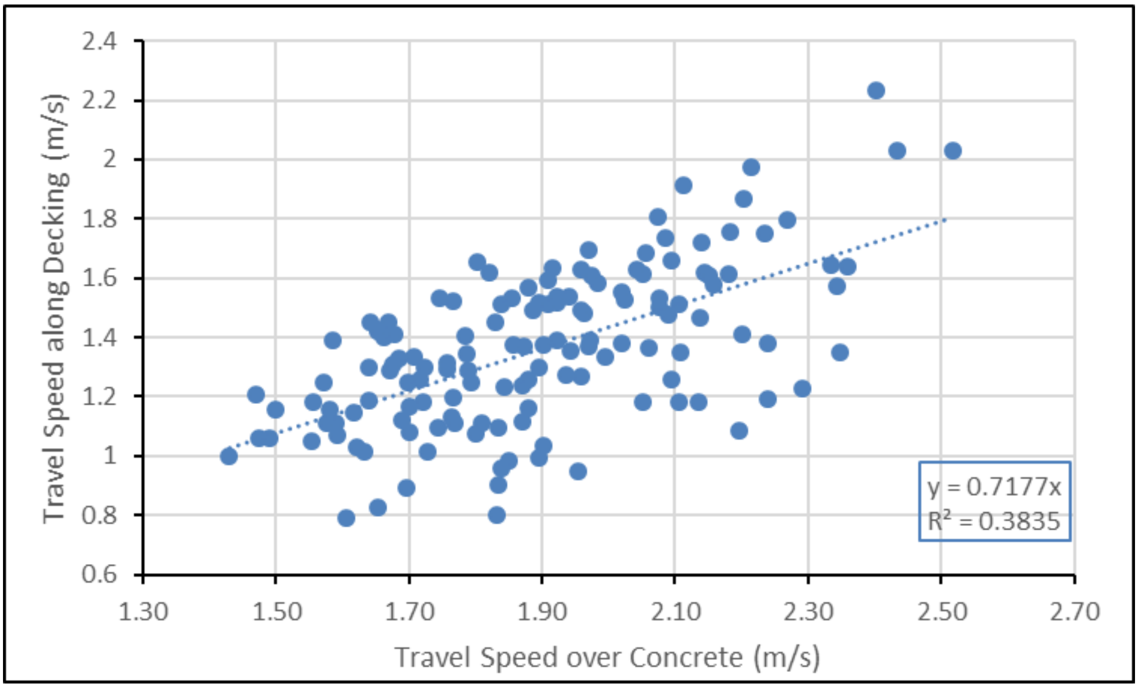


Figure 108. Comparison of individual walking speed along metal decking with walking speed on concrete.

Clearly, there is a relationship between an individual's walking speed on concrete and their walking speed on the other surface types; however, there is also a considerable amount of variation. For example, with a walking speed on concrete of 1.9 m/s, the corresponding walking speed across decking varies from 1.2 m/s to 1.7 m/s. The wide range of variability results in the relatively low correlation achieved (ranging from 0.38 to 0.48) for each of the lines of best fit. The greatest variability, and hence poorest correlation, is for the relationship between walking speeds for concrete and along decking (R^2 = 0.3835), which is also the surface with the lowest speeds on the alternative surface resulting from the greatest difficulty in accommodating the surface.

It is possible that the wide variability in performance is due to worker experience in dealing with the surfaces. The research team, who had zero experience in dealing with these types of surfaces, found walking over the surfaces to be very challenging. Experience on construction sites was one of the parameters measured in the survey developed for the walking trials (see Appendix 1). Experience of walking on the surfaces was measured as less than one month, less than three months, less than one year and greater than one year. Clearly, walking speed on concrete should not be impacted by experience, as everyone on the construction site is expected to be 'experienced' walkers on normal surfaces. Thus for the experienced and inexperienced categories, the walking speed on concrete probability distribution was expected to be both normal (according to the Shapiro-Wilks test) and should be derived from the same distribution (as determined by the t-test). Furthermore, the walking speed probability distributions for the other surfaces for both experience categories (i.e. experienced and inexperienced) should also be normal and should be derived from different distributions (as determined by the t-test). The only experience category that satisfied these conditions was the one-month category. This suggests that within one month of working on a construction site, workers become accustomed to walking over the different types of surfaces.

Based on the one-month experience category, the walking speed distributions are shown in Figure 109 to Figure 112. In Figure 109 (concrete), the experienced category consists of 97 data points, while the inexperienced category consists of 43 data points. In Figure 110 (across decking), the experienced category consists of 97 data points, while the inexperienced category consists of 43 data points. In Figure 111 (rebar), the experienced category consists of 73 data points, while the inexperienced category consists of 40 data points. In Figure 112 (along decking), the experienced category consists of 98 data points, while the inexperienced category consists of 43 data points.

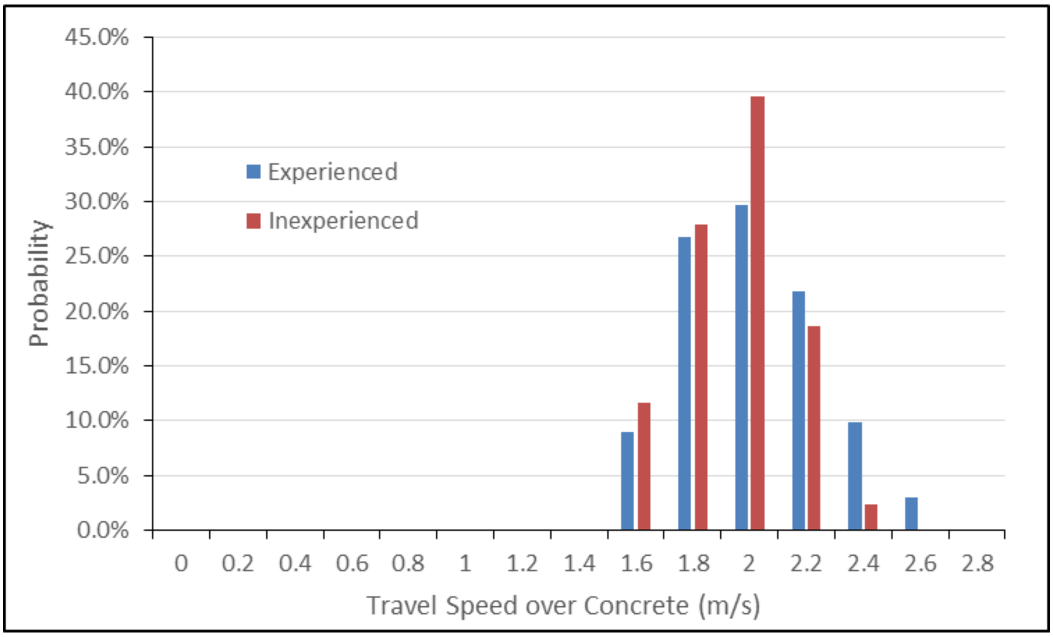


Figure 109. Summary of walking speed trial data for the concrete surface based on experience.

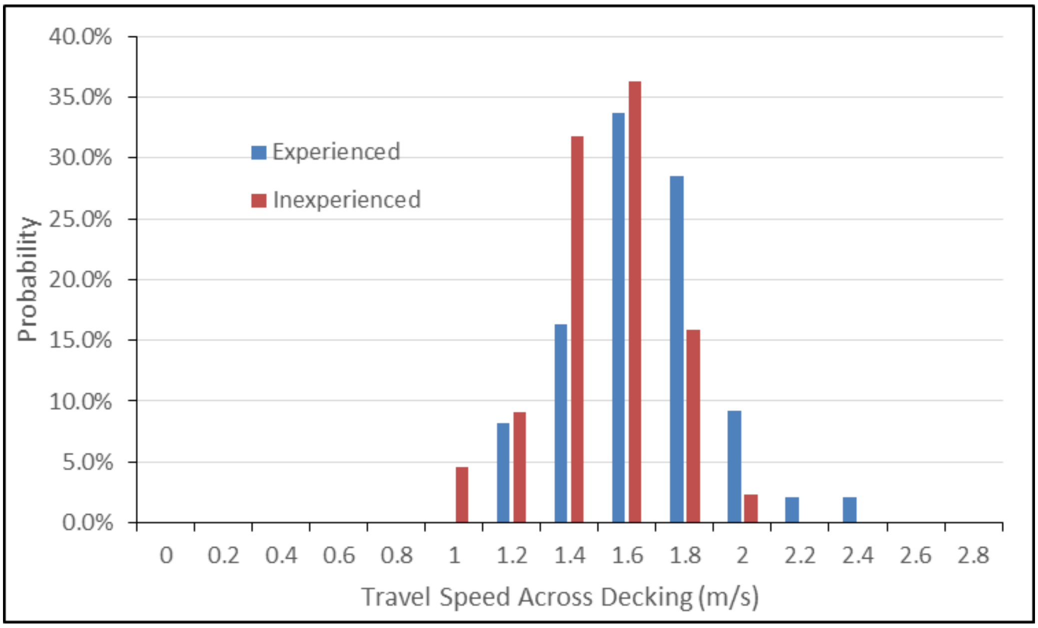


Figure 110. Summary of walking speed trial data for the across decking surface based on experience.

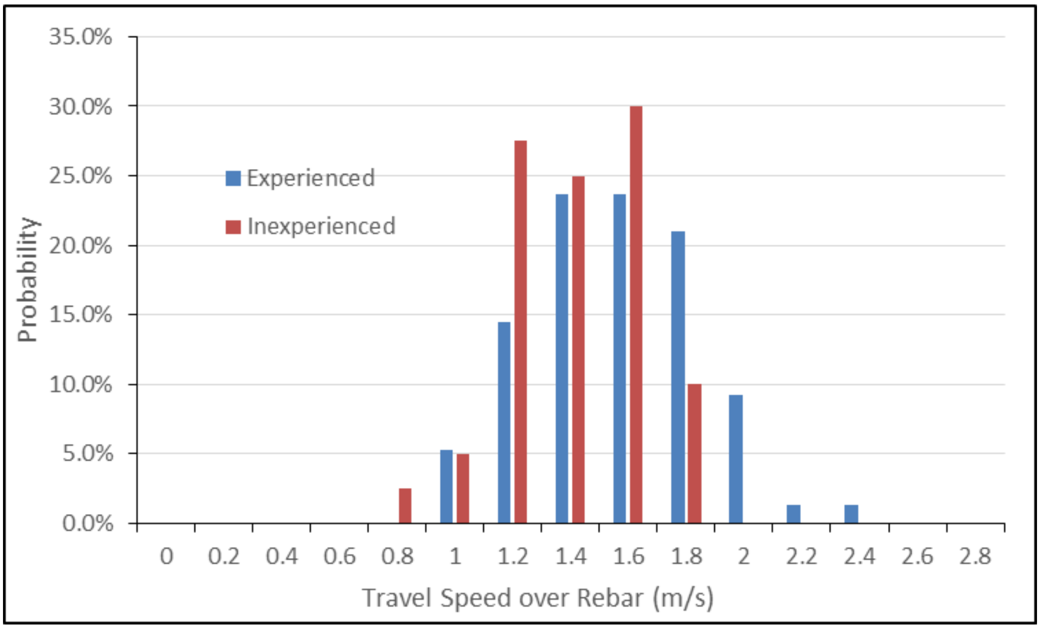


Figure 111. Summary of walking speed trial data for the rebar surface based on experience.

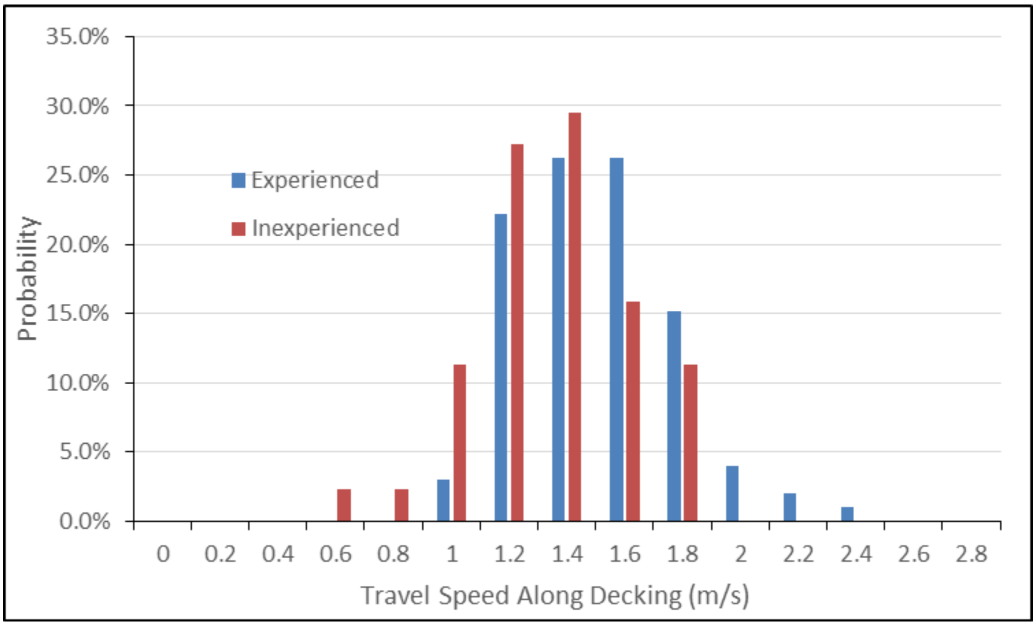


Figure 112. Summary of walking speed trial data for the along decking surface based on experience.

If the scatter plots of walking speeds for each participant over the various surfaces against the walking speed on concrete are redrawn, taking into account experience, this results in Figure 113 to Figure 115.

There are now two best-fit lines: one for experienced workers and one for inexperienced workers. In addition, a third (dotted) line is included which depicts the equality relationship between the two walking speeds. If data points are below this line, this indicates that the speed on concrete is greater than the speed on the other surface.

Finding 8.2: Worker experience and walking speeds on different surfaces – Walking speeds on the different surfaces appear to be impacted by the experience of the worker. Workers with less than

one month's experience of construction sites tend to walk slower on all surfaces, with the exception of concrete, than more experienced workers.

Introducing the experience categorisation has greatly reduced the amount of variation in the data. For example, with a walking speed on concrete of 1.9 m/s, the corresponding variation in walking speed across decking has reduced from a range of (1.2 m/s to 1.7 m/s) to (1.5 m/s to 1.7 m/s) for experienced workers and (1.2 m/s to 1.6 m/s) for inexperienced workers. It is noted that the greater variability in walking speeds on the various surfaces occurs for inexperienced workers.

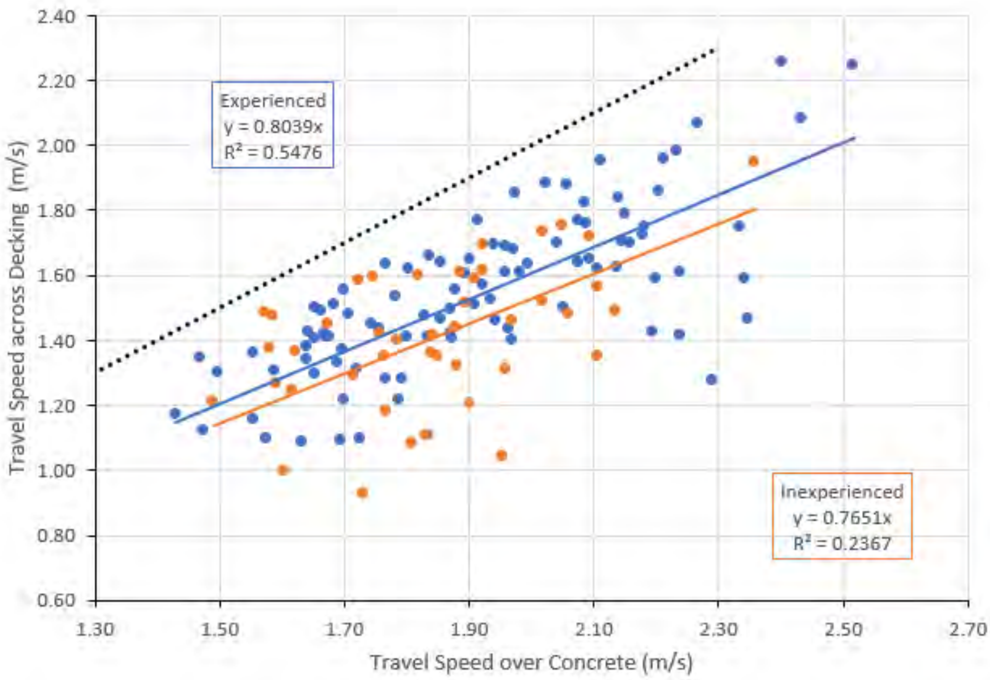


Figure 113. Comparison of individual walking speed across metal decking with walking speed on concrete as a function of experience.

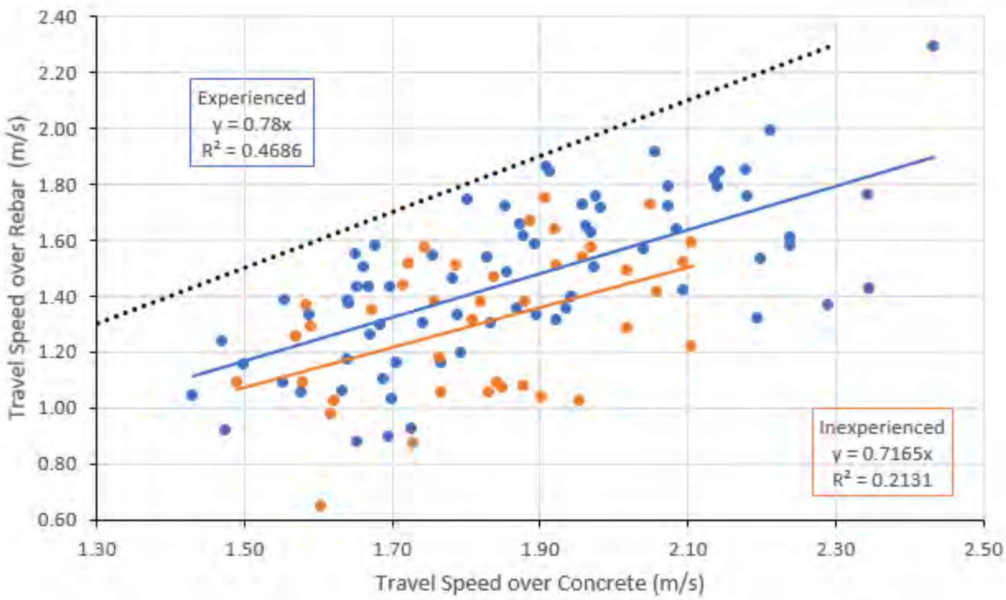


Figure 114. Comparison of individual walking speed on rebar with walking speed on concrete as a function of experience.

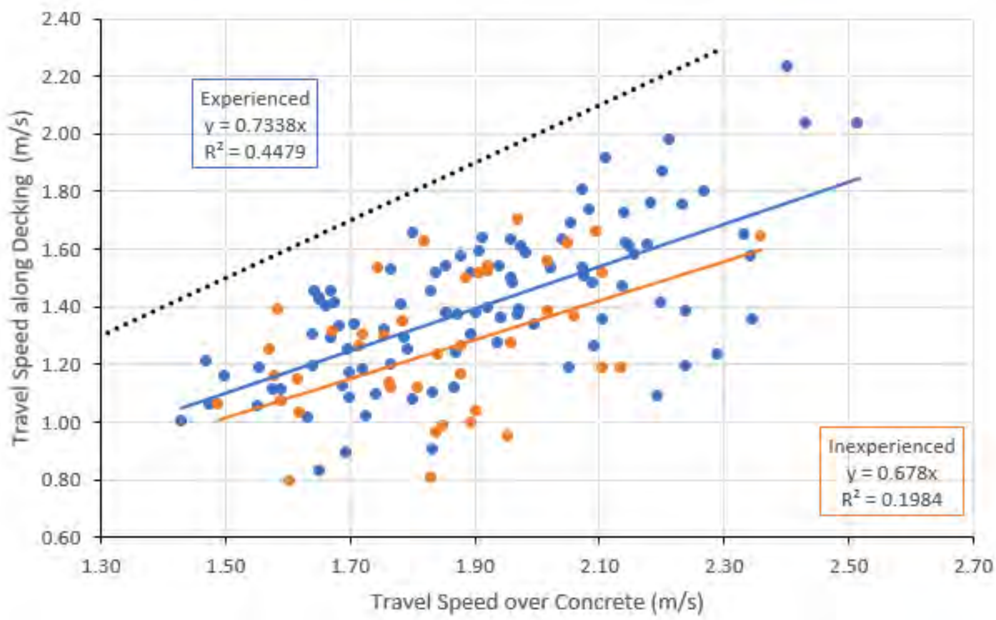


Figure 115. Comparison of individual walking speed along metal decking with walking speed on concrete as a function of experience.

The reduction in variability has improved the correlation values for the experienced category from the original range of (0.38 to 0.48) to (0.44 to 0.55), while the range for the inexperienced has become (0.20 to 0.24). The poorer correlation for the inexperienced is due to two factors: the first is the smaller number of data points in the inexperienced category (there being half as many data points in the inexperienced category as in the experienced category) and secondly, by their very nature, the inexperienced group are expected to display a wider range of walking speeds. Furthermore, the greatest variability, and hence poorest correlation, is for the relationship between walking speeds for concrete and along decking (R^2 = 0.4479 for experienced and 0.1984 for inexperienced), which is also the surface with the lowest speeds on the alternative surface resulting from the greatest difficulty in accommodating the surface.

As can be seen from all three plots, the speed on concrete is always greater than the speed on the other surface. Furthermore, the highest walking speeds of experienced workers are almost always greater than the highest speed of inexperienced workers, and the lowest speeds on the other surfaces are dominated by inexperienced workers. As a result, the best-fit line for experienced workers is always above that of inexperienced workers, which implies that the greatest travel speed reduction factors occur for the inexperienced workers.

Based on the regression lines and data presented in Figure 113 to Figure 115, it is possible to specify the global reduction factors to estimate walking speed on the different surfaces based on the walking speed on concrete (see Table 27). As can be seen from the data in Table 27, walking speeds on the different surfaces can be significantly reduced. In general, we find that

Average speed concrete > average speed across deck > average speed rebar > average speed along deck.

For experienced workers, walking speeds can be reduced by as much as 27%, while for inexperienced workers, walking speeds can be reduced by as much as 32%.

As already noted, the walking speeds of the workers are quite high, on the verge of running speeds. Running on construction sites is not generally permitted as this could lead to slips or trips and is generally considered unsafe. Rather than using the actual walking speeds measured in these trials, it is suggested that the reduction factors are used in evacuation modelling applications.

It is suggested when dealing with a regulatory required or general safety analysis that the walking speed reduction factors for inexperienced workers are used (see Table 27) as these will be more conservative. If using modelling as part of a site-specific analysis, where there are known to be a given proportion of experienced and inexperienced workers on site, but the location of experienced and inexperienced workers is not known, then it is suggested to make use of the ALL speed reduction factor. Finally, if using modelling for a forensic analysis, then it is suggested that wherever possible the experienced and inexperienced speed reduction factors are used as appropriate.

Table 27. Average walking speed data for the four types of surface as a function of experience with global travel speed reduction factors.

Population	Parameter	Concrete	Across decking	Rebar	Along decking
ALL	Average Speed (m/s)	1.89	1.50 (21%)	1.41 (25%)	1.36 (28%)
	Global Reduction Factor	-	0.79	0.76	0.72
Experienced (> 1 month)	Average Speed (m/s)	1.91	1.54 (19%)	1.47 (22%)	1.41 (27%)
	Global Reduction Factor	-	**0.80**	**0.78**	**0.73**
Inexperienced (< 1 month)	Average Speed (m/s)	1.85	1.41 (23%)	1.31 (28%)	1.25 (32%)
	Global Reduction Factor	-	**0.76**	**0.72**	**0.68**
Difference btw exp and inexp	Average Speed	3.1%	8.4%	10.9%	11.3%
	Reduction Factor	0.97	0.92	0.89	0.89

Key Finding 8.1: Generalised walking speed based on surface type – A generalised set of walking speed reduction factors has been developed that when combined with the walking speed on concrete can be used to estimate a walking speed when walking across decking, along decking or on decking with rebar. The reduction factors are dependent on the experience of the worker, where inexperienced workers have a greater reduction in walking speed imposed than experienced workers. On average, walking speeds on concrete are greatest followed by, in reducing speed order, across decking, rebar and along decking. For inexperienced workers, walking speeds along decking can be as little as 68% of the walking speed on a concrete surface. It is recommended that the inexperienced reduction factors are used when dealing with a regulatory required or general safety analysis as this represents the greatest reduction in walking speeds over each of the surfaces and so is more conservative.

4.8.2 Vertical walking speeds up and down scaffold temporary dogleg and parallel staircases

There are two different types of temporary scaffold stairs used on construction sites: dogleg (see Figure 17a) and parallel stairs (see Figure 17b). Presented in Figure 116 to Figure 119 are the distributions of walking speed data extracted from the experiments for each of the stairs: dogleg up (Figure 116), dogleg down (Figure 117), parallel up (Figure 118) and parallel down (Figure 119). These distributions are based on 69 data points (dogleg up), 73 data points (dogleg down), 53 data points (parallel up) and 53 data points (parallel down). Each speed was determined over a single flight of stairs, represents the unhindered speed and only considers the speed on the stairs. Also, the travel speeds are determined using the distance down the slope of the stair.

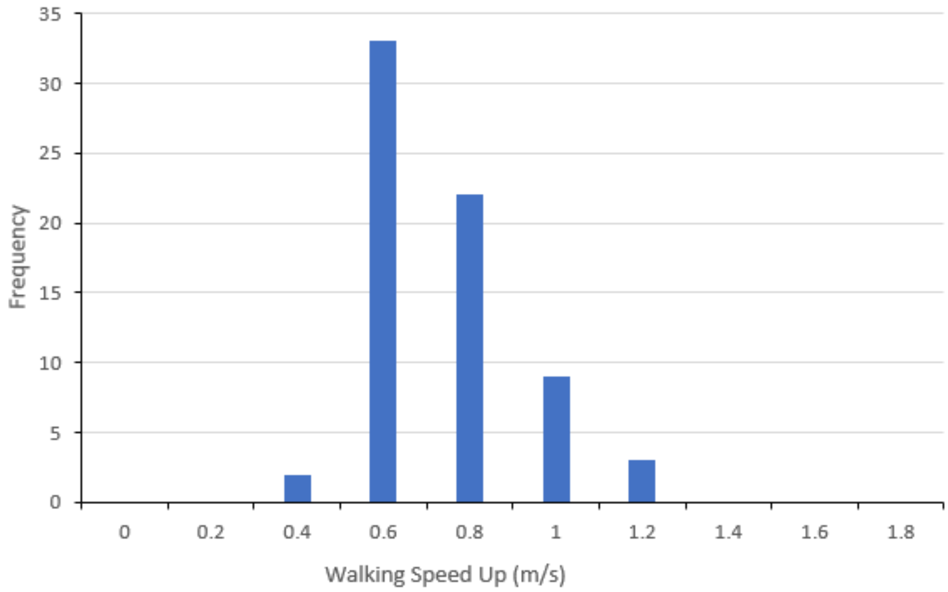


Figure 116. Walking speed up the dogleg stair.

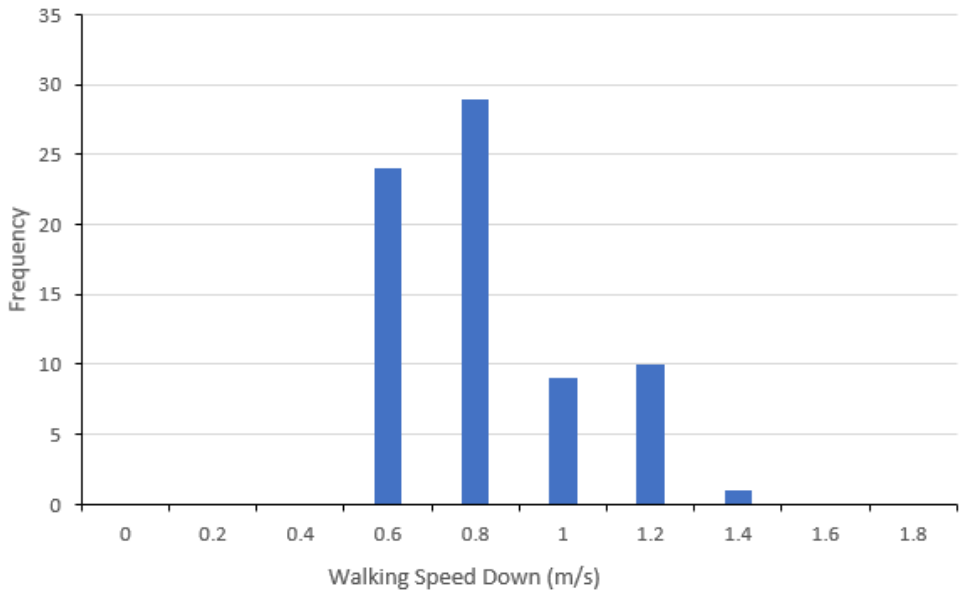


Figure 117. Walking speed down the dogleg stair.

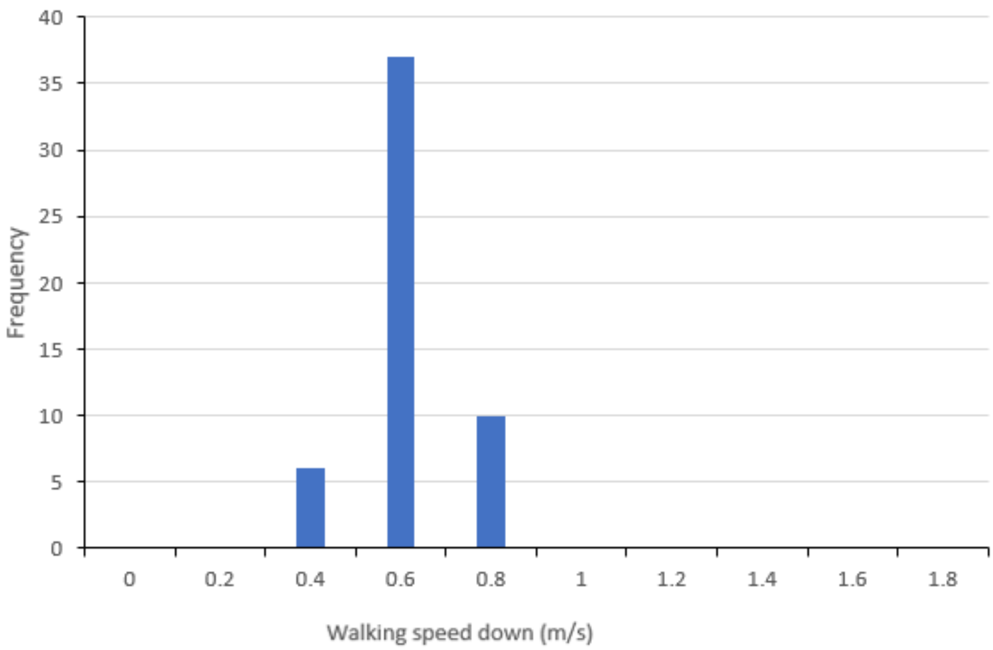


Figure 118. Walking speed up the parallel stair.

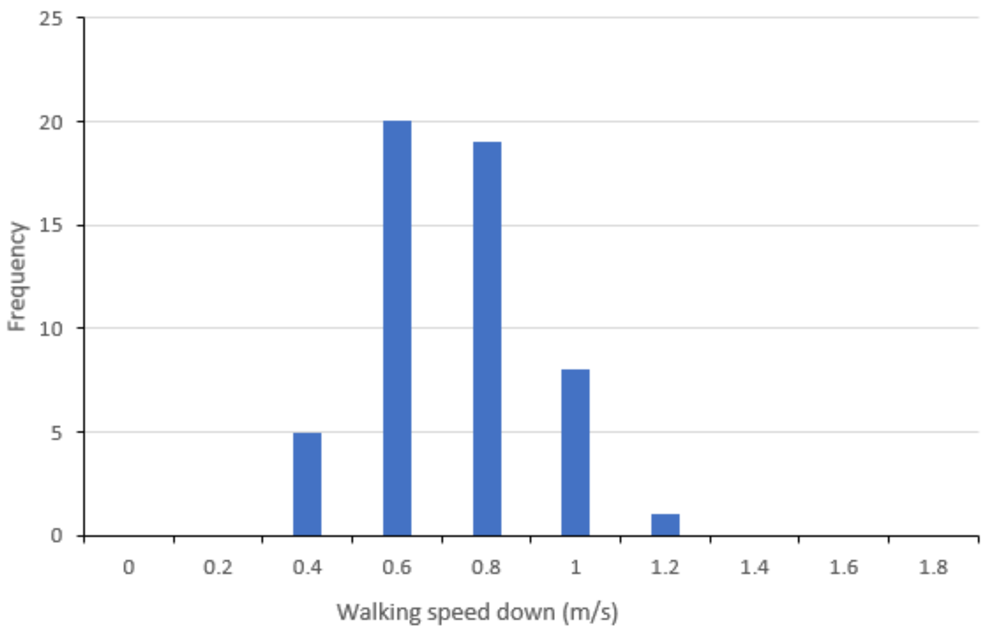


Figure 119. Walking speed down the parallel stair.

Presented in Table 28 are the basic statistics for travel speeds on both types of temporary stairs. As can be seen, walking speeds ascending and descending the dogleg stair are greater than the equivalent speeds for the parallel stairs. The average ascent speed on the dogleg stair is 26% greater than the average ascent speed on the parallel stairs, while the average descent speed on the dogleg stairs is 13% greater than the average descent speed on the parallel stairs. In addition to the slower speeds on the parallel stairs compared to the dogleg stairs, stair users will need to traverse a much longer landing when transferring from one flight to the next. As a result, for the same vertical drop traversed using dogleg and parallel stairs, the dogleg stair is much more efficient and so more desirable for evacuation. However, parallel stairs may offer other practical benefits such as they can fit into a smaller available space than a dogleg stair (total width of dogleg stair is greater than the width of a single flight of parallel stair plus landing) and have better configuration of access points (parallel stairs offer more frequent access points, i.e. at the end of each flight and access can be at either end of the landing).

Table 28. Summary of ascent/descent speeds on temporary stairs.

	Dogleg		Parallel	
	Ascent (m/s)	Descent (m/s)	Ascent (m/s)	Descent (m/s)
Minimum	0.38	0.42	0.33	0.36
Mean	0.63	0.72	0.50	0.64
Maximum	1.10	1.21	0.75	1.15
Standard Deviation	0.18	0.21	0.10	0.16

Presented in Table 29 and Table 30 are the descent and ascent speeds on temporary scaffold dogleg stairs, temporary scaffold parallel stairs, ladders and standard building stairs. The distributions for the speed on various devices are also presented graphically in Figure 122 and Figure 132, which show the modal ascent speed for both dogleg and parallel temporary stairs is 0.6 m/s while the modal descent speed for dogleg temporary stairs is 0.8 m/s, for parallel stairs and ladders 0.6 m/s.

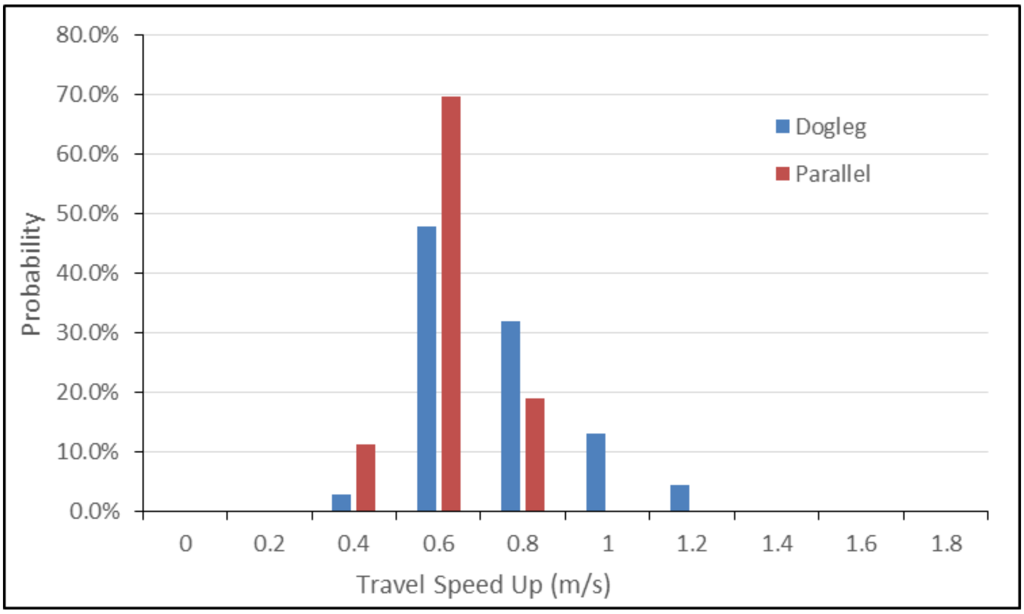


Figure 120. Comparison of ascent travel speeds for the dogleg and parallel temporary scaffold stairs.

As can be seen the workers on temporary dogleg scaffold stairs have the same average ascent performance as males (30 to 50) on regular stairs but their descent speed is 84% of the corresponding stair speed (see Table 29 and Table 30). Compared to standard stairs, parallel stairs produce average descent and ascent speeds that are 74% and 79% of the corresponding stair speeds, while ladders produce average descent and ascent speeds that are 52% and 67% of the corresponding stair speeds.

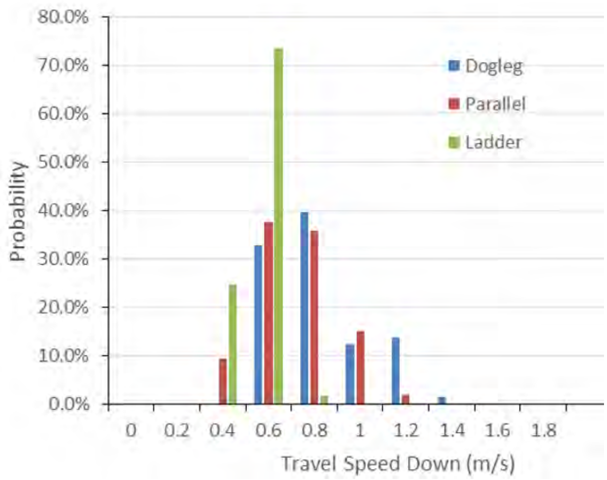


Figure 121. Comparison of descent travel speeds for the dogleg and parallel temporary scaffold stairs and ladders.

Table 29. Descent speed on various devices.

	Dogleg stairs (m/s)	Parallel stairs (m/s)	Ladder (m/s)	Standard stairs average (Fruin) (m/s)
Min	0.42	0.36	0.29	(Male 51–80) 0.67
Average	0.72	0.64	0.45	(Male 30–50) 0.86
Max	1.21	1.15	0.61	(Male 17–29) 1.01

Table 30. Ascent speed on various devices.

	Dogleg stairs (m/s)	Parallel stairs (m/s)	Ladder (m/s)	Standard stairs average (Fruin) (m/s)
Min	0.38	0.33	0.39	(Male 51–80) 0.51
Average	0.63	0.50	0.42	(Male 30–50) 0.63
Max	1.10	0.75	0.44	(Male 17–29) 0.67

Key Finding 8.2: Walking speeds on temporary stairs – The average ascent speed of workers on temporary scaffold dogleg stairs and standard building stairs are very similar while the descent speed is 84% of the corresponding building stair speed. A significant difference between the two is the width of the stairs, which for scaffold stairs is very narrow, only allowing a single person per tread. Thus overtaking or contraflow is not possible on these stairs. The device which offers the next fastest performance, in both ascent and descent, is the parallel stair, with the ladder representing the device producing the slowest speeds. The average descent speed on parallel stairs is 74% of the stair descent stair speed for normal building stairs and the ascent speed is 79% of the normal stair ascent speed, while for ladders, the average descent and ascent speeds are 52% and 67% of the corresponding normal building stair speeds. It should be noted that the temporary stair/ladder data has limitations due to the relatively small number of data points available, especially for the ladder ascent (only two data points) and that the speeds on the temporary stairs were determined over just a single flight, so issues such as fatigue are not considered.

For evacuation modelling purposes the same age range as that used in the Fruin stair speeds will be assumed applicable to the temporary dogleg stairs. However, as age ranges were not monitored during the trials it is assumed that the minimum derived speeds will be applied to the upper age range and the maximum derived speeds will be applied to the younger age range. This simplification is a mechanism to enable a range of speeds to be employed for the temporary stairs that are consistent with that used for the standard stairs. It is, however, reasonable to assume that the faster speeds are likely to be achieved by younger individuals and slower speeds achieved by older individuals. Where the speed measured in the trial exceeds the speed on normal stairs, the speed from the normal stairs will be imposed in preference to the greater speed. This means that the imposed speeds are more conservative than suggested by the trial results. The same approach is adopted for ladder speeds, but in this case the actual speeds derived from the trials are imposed unless the trial speed is greater than the standard stair speed. The suggested ascent/descent speeds for use in modelling for dogleg and parallel temporary scaffold stairs and ladders are presented in Table 31 and Table 32. Alternatively, the speed distributions depicted in **Error! Reference source not found.** and **Error! Reference source not found.** may be imposed on the simulations.

Table 31. Imposed model descent speed on various devices.

	Dogleg stairs (m/s)	Parallel stairs (m/s)	Ladder (m/s)	Standard stairs average (Fruin) (m/s)
Male 51–80	0.42	0.36	0.29	0.67
Male 30–50	0.72	0.64	0.45	0.86
Male 17–29	1.01	1.01	0.61	1.01

Table 32. Imposed model ascent speed on various devices.

	Dogleg stairs (m/s)	Parallel stairs (m/s)	Ladder (m/s)	Standard stairs average (Fruin) (m/s)
Male 51–80	0.38	0.33	0.39	0.51
Male 30–50	0.63	0.50	0.42	0.63
Male 17–29	0.67	0.67	0.44	0.67

4.8.3 Summary of key findings from walking speed experiments.

The walking speed experiments have produced a range of data to represent the walking speeds of workers over the three different floor surfaces, i.e. concrete, decking and decking with rebar, and the two different configurations of temporary scaffold stairs: dogleg and parallel.

- A generalised set of walking speed reduction factors has been developed that when combined with the walking speed on concrete can be used to estimate a walking speed when walking across decking, along decking or on decking with rebar. The reduction factors are dependent on the experience of the worker, where inexperienced workers have a greater reduction in walking speed imposed than experienced workers. On average, walking speeds on concrete are greatest followed by, in reducing speed order, across decking, on rebar and along decking. For inexperienced workers, walking speeds along decking can be as little as 68% of the walking speed on a concrete surface. It is recommended that the inexperienced reduction factors are used when dealing with a regulatory required or general safety analysis as this represents the greatest reduction in walking speeds over each of the surfaces and so are more conservative.

- The average ascent speeds of workers on temporary scaffold dogleg stairs and standard building stairs are similar while the average descent speed is 84% of the descent speed for standard building stairs. The device which offers the next fastest performance, in both ascent and descent, is the parallel stair, with the ladder representing the device producing the slowest speeds. The average descent speed on parallel stairs is 74% of the stair descent speed for normal building stairs and the ascent speed is 79% of the normal stair ascent speed, while for ladders, the average descent and ascent speeds are 52% and 67% of the corresponding normal building stair speeds respectively. It should be noted that the temporary stair/ladder data has limitations due to the relatively small number of data points available, especially for the ladder ascent (only two data points), and that the speeds on the temporary stairs were determined over just a single flight, so issues such as fatigue are not considered.

4.9 Summary of the main results

In this section the data from the four full-scale evacuation trials and the five walking speed experiments were analysed. The data-set generated from these nine trials involving 1,072 participants incorporates around 2,200 data points. The analysis of this data has produced generalised distributions for:

- response times for workers in the jumpform
- response times for workers in the main building
- walking speeds over different types of surfaces found on working sites, e.g. decking
- ascent/descent speeds of workers on ladders
- ascent/descent speeds of workers on temporary scaffold stairs (arranged as dogleg and parallel).

In addition, the analysis has shed light on construction worker behaviour related to:

- risk perception
- influence of construction height on response times
- influence of work type on response times
- performance on temporary stairs.

Presented in Table 33 is a summary of the main evacuation results. As can be seen, the average response times for workers in the formworks varied from 29 s to 58 s, while the average response time for workers in the main building varied from 62 s to 76 s. Total evacuation times varied from 9 m 14 s to 20 m 47 s depending on height of construction and number of workers, with exit flows varying from 0.08 p/s to 0.32 p/s. The low exit flow in Trial 2 was due to the majority of workers (30 of the 43) being located in the formworks, resulting in a few workers exiting early (those located low down in the main part of the building) while the majority exited later. Ignoring this value, the exit flows achieved in the trials where the workers are distributed throughout the building varied from 0.25 p/s to 0.32 p/s, with a weighted mean exit flow of 0.29 p/s.

Table 33. Summary of key results from the four full-scale unannounced evacuation trials.

Trial and date	Location	Number of workers	Core level	Average formworks RT(s)	Average main building RT(s)	Total evacuation time (s)	Average exit flow (p/s)
Trial 1 14/02/17	100 BG	184	19	29	76	766 (12 m 46 s)	0.25
Trial 2 28/02/17	22 BG	43*	13^{X}	56	-	554 (9 m 14 s)	0.08
Trial 3 04/10/17	100 BG	308	38	-	62	1,098 (18 m 18 s)	0.29
Trial 4 16/11/17	22 BG	388	32^{X}	58^{+}	75	1,247 (20 m 47 s)	0.32

*: Excludes 3 workers from the South Core, ^{X}: North Core, $^{+}$: Excludes 6 supervisors.

The conclusion of this section describes the successful completion of project Task 3 addressing the requirements of project Objectives 1 to 3.

5 Task 4 – model calibration and validation

In this section data from the four full-scale evacuation trials and five walking speed experiments are used to define a validation data-set that can be used to examine how accurately evacuation models can predict an actual evacuation from a high-rise construction site. Along with the validation data-set, the uncertainties in the data-set are identified in order to assist in specifying the level of acceptable agreement between model prediction and experimental data. Objective performance metrics are defined to measure the level of agreement between model predictions and experimental data, and finally, predictions from the buildingEXODUS evacuation model are compared with the validation data-set to demonstrate how well the model can reproduce the actual evacuation.

5.1 The validation data-set

An evacuation validation data-set can be used to gauge the ability of an evacuation software tool to represent the particular behaviour and evacuation performance for a particular scenario. The data-set presented here is intended to represent some of the specific issues associated with construction sites and so has geometric-specific features that will impact performance, e.g. floor surface types, nature of temporary stairs, presence of ladders; procedural-specific issues that will impact performance, e.g. restricting flow on temporary stairs; population-specific issues that will influence performance, e.g. initial population distribution; and behavioural specific issues, e.g. response time distributions.

Once these features are specified, the ability of the software tool to accurately and reliably reproduce the evacuation scenario can be gauged by comparing the model predictions with the results from the trials. The comparisons are not simply restricted to the total evacuation time, but to evacuation curves generated at key locations within the building, the most important being the exit curve. However, other key locations can also be considered; for the construction site, this may, for example, include the exit curve from the formworks.

Finally, whether or not the model predictions are considered to be a good representation of the experimental data must be determined in an objective way. This is achieved by defining a performance metric which measures the level of agreement between the model predictions and the experimental data. However, the level of acceptability must take into consideration uncertainties that may exist within the experimental data-set. This uncertainty is usually not associated with the key comparison data, i.e. the exit curves, but in defining initial conditions such as the starting location and the response times of the workers, and other key data related to the specific paths taken by the occupants.

Defining an appropriate validation data-set requires a considerable amount of initial data defining the starting or initial conditions for the trial. This must include an accurate description of the geometry, the total number of people within the building, their initial distribution and response times. The data-set should also include the exit curve (or curves if several key monitoring locations are identified) for the trial.

Of the four unannounced full-scale trials conducted, Trial 4 provided the most complete data-set for consideration of creating a validation data-set. The construction site at 22 BG essentially had one vertical exit route from each floor, greatly simplifying the process of collecting sufficient accurate data to define a validation data-set. Furthermore, unlike Trial 2 (which was also at 22 BG), Trial 4 had more workers on site and these were distributed throughout the building and not just in the formworks as in Trial 2. Furthermore, the building in Trial 4 extended over 39 levels (in the South Core) and 33 levels (in the North Core) with 20 levels in the process of being constructed. Although there were insufficient cameras to cover all floors of the construction site, there were enough to obtain a reasonable level of granularity in terms of starting floor for workers.

In total there were 388 workers in the building during Trial 4, but only 82 response times were collected from this trial (see Section 4.4). As a result, there is considerable uncertainty to be expected in the response times used to specify the validation data-set.

5.1.1 The building geometry

5.1.1.1 Specifying the building geometry

The building geometry for the validation data-set is based on the North Core of 22 BG and was specified using CAD drawing provided by Multiplex (see Figure 138). The geometry includes 33 levels above the ground. Level 1 to Level 20 are complete or partially complete levels, while Level 21 to Level 32 are core only with the jumpform at Level 33. The building layout is summarised in Figure 122. The vertical means of egress consisted of permanent stairs (P), temporary stairs (T), hanging stairs (H) and ladders.

The permanent staircase (see 'P' in Figure 122):

- extends from the ground floor (Level 0) to Level 8 (see Figure 15a)
- has dimensions of 1,260 mm wide (clear width), 2,750 mm horizontal run and a drop of 2,000 mm, with rise height of 168 mm and tread depth of 250 mm
- the stairs consist of a flight of 11 treads with a landing followed by a second flight of 11 treads
- at the base of the staircase on the ground floor is the exit point for the building
    - located on Level 3 is the cafeteria, offices and changing facilities
    - at the Level 3 landing there is a small gate sufficiently wide to allow only one person at a time to enter/exit the flight. The gate is directly in the path of the workers who step through the gate as they step off the last tread on the stair (see Figure 123)
    - on reaching Level 3, workers can pass through the gate, and either exit the stair and walk along a narrow corridor to enter the staff facilities or continue down the stairs
    - for the purposes of the validation case, the exit to the stair on Level 3 is the evacuation end point. Workers are counted as exiting the building once they pass through the gate at the end of stair flight on Level 3 (see Section 5.1.5.1).

On Level 8, the permanent staircase ends and a temporary scaffold begins (see 'T' in Figure 122):

- the stair type is dogleg
- extends from Level 8 to Level 28 (part of the stair is internal to the building and part is external)
- from Level 8 to 18 it is internal
    - has dimensions of 700 mm wide (clear width), 1,700 mm horizontal run and a drop of 2,000 mm, with a riser height of 200 mm and a tread depth of 189 mm and a total of 9 treads per flight
    - as workers exit onto Level 8 from the internal temporary stair, they are just outside the core and must walk 12 m to enter the permanent stairs within the core
- from Level 18 to 28 the temporary stair is external (see Figure 124).

On Level 28, up to the jumpform is the hanging stair (see 'H' in Figure 122):

- the stair is a temporary scaffold stair of dogleg type
    - has dimensions of 700 mm width (clear width), 1,700 mm horizontal run and a drop of 2,000 mm with a riser height of 200 mm and a tread depth of 189 mm with 7 treads per flight (see Figure Figure 125)
    - as workers exit onto Level 28 from the external temporary stair, they are located just outside the core and must walk 6 m into the core to enter the hanging stair

- extends from Level 28 up to the top of the jumpform at Level 34 (jumpform is at Level 33, but top of the jumpform is at Level 34).

Within the jumpform, there are two ladders (marked as 'L' in Figure 126), each of which extend from the lower deck to the upper deck. They are located in the south-east corner and the north-west corner of the jumpform, as depicted in Figure 126.

The height between floors in the main building was 4 m.

Ground floor (Level 0)

Levels 1–17

Level 18

Figure 122. Building floor plans for the construction site validation data-set showing the location of permanent (P), temporary (T) and hanging (H) staircases.

Figure 123. Gate at base of flight on Level 3. The yellow top of the gate can be seen in the top half of the red circle.

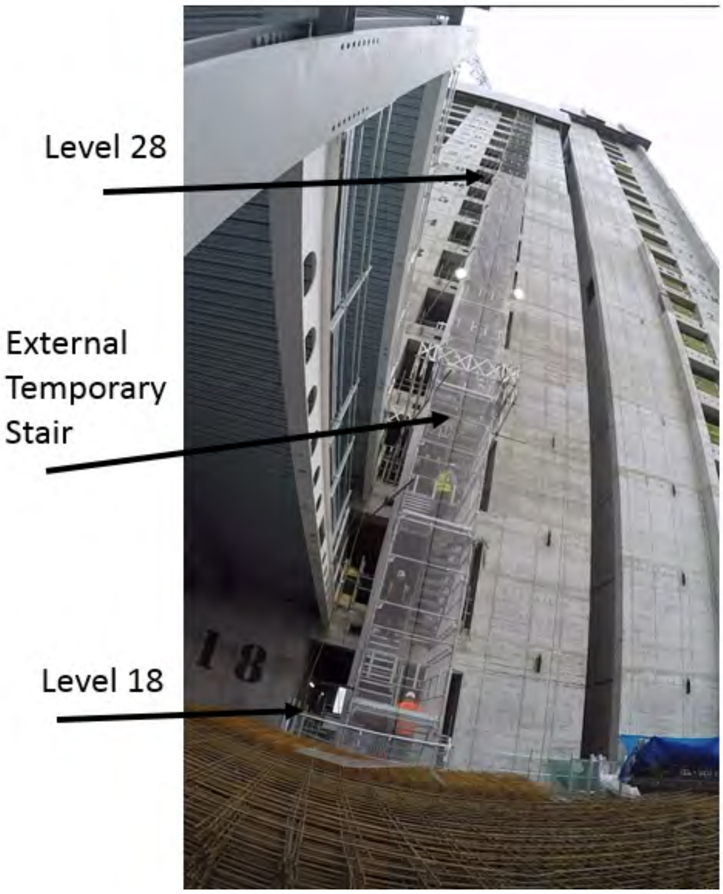


Figure 124. External scaffold dogleg temporary stairs.

The jumpform at Level 33 consisted of two main decks, a bottom (located at Level 33) and a top deck (located at Level 34), with a hanging deck located between the two. Workers could be positioned on any of the three decks. The exit from the jumpform is via the hanging stairs. The only entrance to the hanging stairs was on the top deck of the jumpform. Workers on the lower deck had to climb up one of two ladders to reach the upper deck and hence the hanging stair. Workers on the hanging deck had to climb down a short ladder to the lower deck and then up to the upper deck via one of two ladders.

On all the other levels workers could enter the external temporary stairs, the internal temporary stairs and permanent stairs directly from their floors.

At the time of the evacuation the nature of the floor surfaces were as follows:

- concrete from Level 1 to Level 14
- decking with rebar from Level 15 to Level 16
- decking from Level 17 to Level 20
- partial decking from Level 21 to Level 22 (steel framework with some decking on).

In addition, some parts of various floors were essentially closed off due to the presence of equipment or construction materials. Some areas were netted off making it necessary to go around the region affected. Apart from the jumpform, the locations of these regions were not recorded.

Figure 125. Hanging scaffold dogleg stairs.

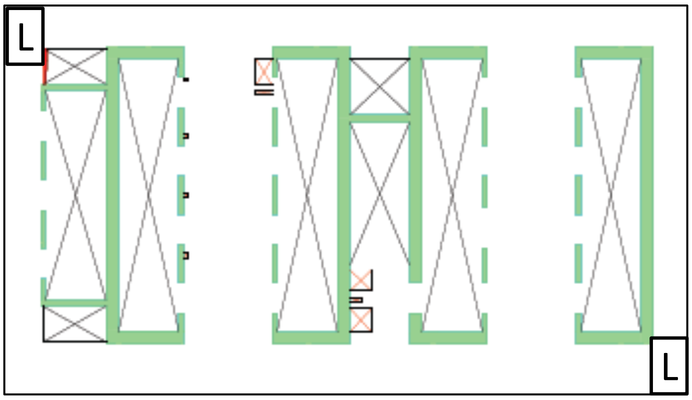


Figure 126. Jumpform showing location of ladders (L) connecting decks.

The nature of the jumpform upper deck layout, including the presence of clutter, is depicted in Figure 127, along with the representation within the buildingEXODUS model. Presented in Figure 128 is the layout of the lower deck of the jumpform that was used in the buildingEXODUS geometry. For the lower deck, only the location of the concrete walls defining the core layout are represented.

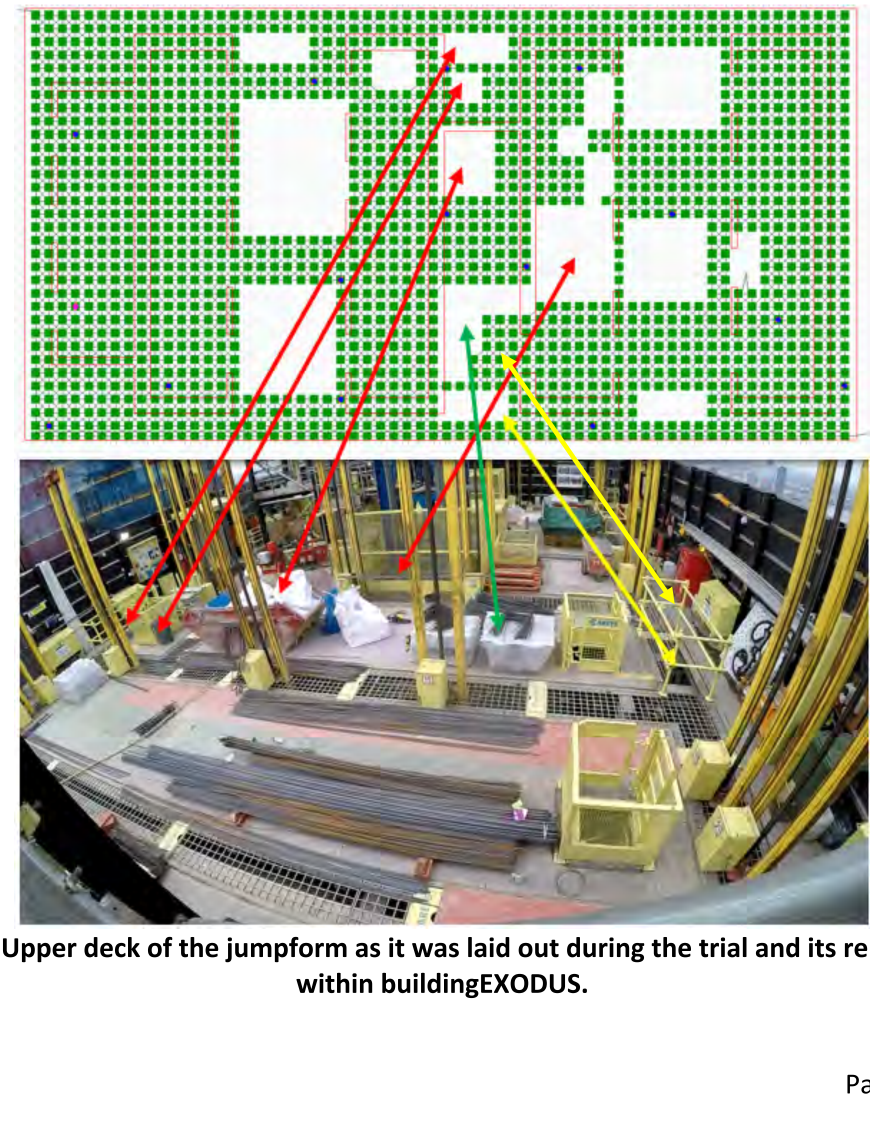


Figure 127. Upper deck of the jumpform as it was laid out during the trial and its representation within buildingEXODUS.

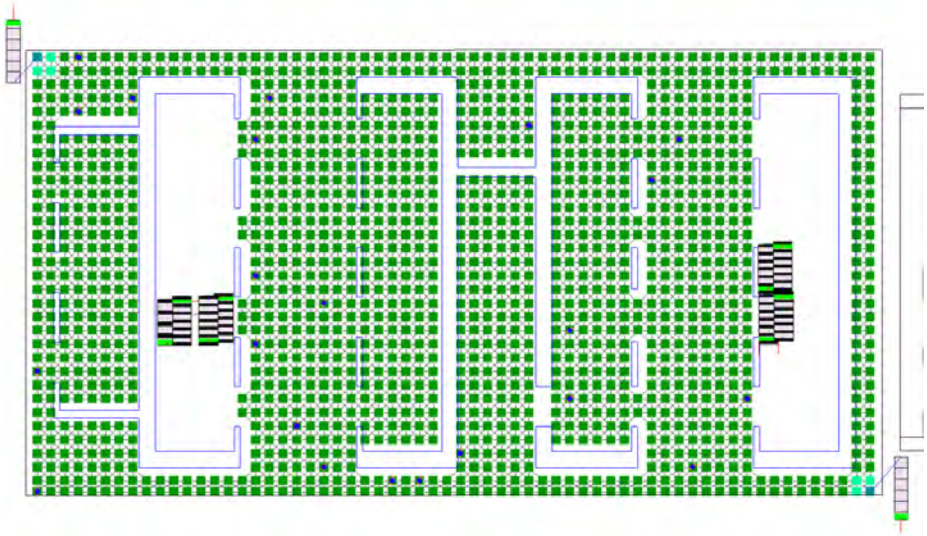


Figure 128. Lower deck of the jumpform represented within buildingEXODUS.

5.1.1.2 Uncertainties in the building geometry

The building geometry is specified to a reasonably high level of certainty. However, a key issue is the missing information about the complexity and layout of the internal clutter on each floor that have an impact on travel distances (and hence travel times) from workers' starting location to the entrance to the means of vertical evacuation. With the exception of the jumpform, these are not represented in the geometry. The presence of the clutter on the various floors is likely to increase the evacuation time of workers as they may have to adopt a circuitous route to the exit point on each floor. Without this clutter, it is likely that the evacuation times produced by the simulations will under-predict the measured evacuation times. Hence not knowing the location of the clutter on the various floors introduces some uncertainty into the validation data-set.

5.1.2 The building population

5.1.2.1 Specifying the building population

As described in Section 4.4.3, there were 388 workers who evacuated from the construction site of 22 BG in Trial 4. In addition, the generalised response time distribution for the formworks excludes six long response times incurred by the supervisors within the jumpform in Trial 4 (see Section 4.6.1). For the same reason, they are excluded from the population for the validation data-set. The population with these six supervisors removed is called the ***Generalised Population*** and consists of 382 workers. The exit times for these six supervisors are also be removed from the exit data-set (see Section 5.1.5). The population consisted of predominately males with an age range of approximately 18 to 65 years of age.

Once the size of the population has been determined, it is important to determine the initial location of the individual workers. As there were insufficient cameras to completely cover each floor, the estimation of starting position is limited to each floor, hence introducing some uncertainty into the validation data-set.

Furthermore, the number of available video cameras placed on the stairs (i.e. four video cameras) do not enable the precise floor for many of the workers to be identified. These cameras revealed not only the number of people coming off the floor they were mounted on, but also identified how many workers were coming down the (only) stairs from above. Using this information, it is possible to identify the floor or zone of floors that the workers originated from. The deduced starting floors for the 388 workers in Trial 4 are presented in Table 34.

Table 34. Deducted location of the specific population in Trial 4.

Building level	Number of workers initially located on the identified level
Formworks – Upper deck (34)	21*
Formworks – Lower deck (33) and hanging deck	22+
28–32	3
22–27	0
21	2
20	14
19	2
18	18
9–17	49
8	12
7M	0
7	15
4–6	75
3	102
1–2	53
Total	**388**

*: These include the 6 supervisors. +: These include workers on both the hanging and lower decks.

Note, located on Level 3 were the staff canteen, office-based construction site staff, lockers and changing rooms. Response times for these type of activities were not captured by this project and so the activities of these workers cannot be represented in the validation data-set, and therefore it was decided to restrict the validation data-set to workers located above Level 3 (see Section 5.1.4 and Section 5.1.5). Also note that the six supervisors in the jumpform were excluded in the validation analysis. With the two subpopulations subtracted from the 388 workers, the total building population within the validation data-set is 277. This includes 37 workers initially located in the jumpform and 190 workers initially located in the main building from Level 4 to Level 32.

It should be noted that although the 155 workers initially located on Level 1 to Level 3 were excluded from the validation analysis, their presence may cause congestion at the stairs on Level 3, effectively delaying the 'exit' of the workers descending from higher up in the trial. Therefore, these workers were included in the setup of the simulation model used for the validation analysis (see Section 5.3.2).

5.1.2.2 Uncertainties in the building population

The precise location of each worker on a floor is unknown. This creates uncertainty in times to join the exit stair. To a limited extent this uncertainty can be addressed by running multiple simulations with randomised starting locations. In this way a range of evacuation times can be determined.

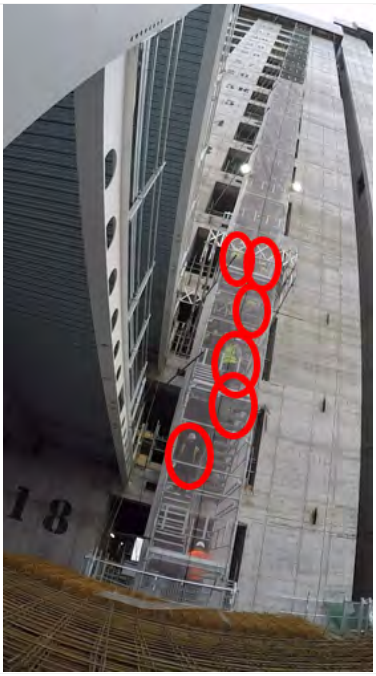
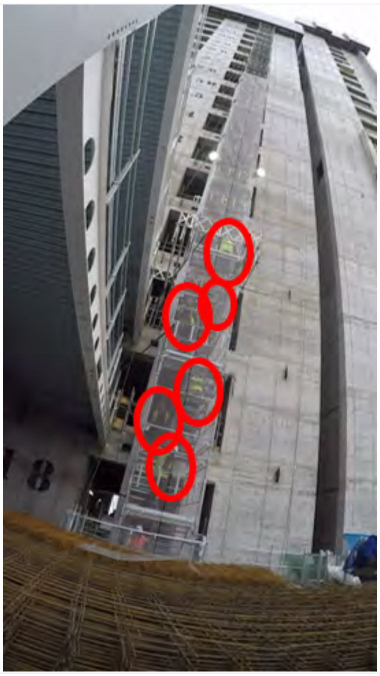
Another difficulty is that in some situations it was not possible to identify the precise floor that workers were initially located on. In these cases, the number of workers and the range of floors over which they are distributed are specified in Table 34. The largest uncertainty occurs from Level 9 to Level 17 where some 49 workers were located. To a limited extent, this uncertainty can be addressed by running multiple simulations and randomising the starting locations of these 49 workers on the identified levels. In the formworks, there were no cameras located in the middle hanging deck and so it is not possible to determine the number of workers located there.

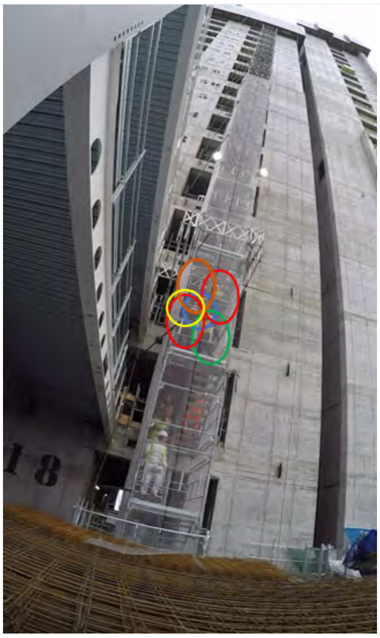
5.1.3 The building evacuation procedures

5.1.3.1 Specifying the building procedures

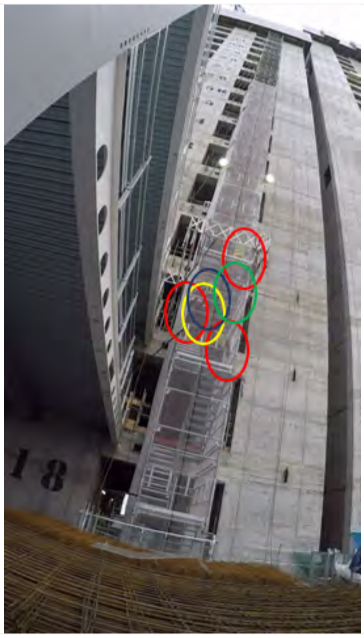
Two sets of specific evacuation procedures were in place for workers in the formworks. To exit the formworks, workers located on the lower deck had to climb up one of the two ladders to reach the upper deck where they could transfer to the hanging stairs. Workers located on the mid hanging deck had to climb down one of several ladders to the lower deck and then make their way up to the upper deck. Unfortunately, the hanging deck was not monitored and so it is not known how many workers were located on this level.

Once workers descended down the hanging stairs and walked across to the top of the temporary external stairs on Level 28, a supervisor regulated the flow of workers onto the stairs. This is understood not to be a normal procedure on the building site but was an ad hoc procedure implemented by a supervisor. The supervisor allowed approximately six workers to enter the temporary stairs approximately every 60 s. Occasionally smaller groups would be allowed through; for example, the first two groups consisted of three workers each. Regulating the flow onto the temporary stairs also had the effect of workers entering the stairs as a group, bunching together and on the whole remaining together as a group as they descended. Shown in Figure 129 are the first six groups allowed down the stairs at various times during their descent. As can be seen, the workers did not tend to walk at their desired speed; rather, they regulated their speed so as to remain together on the stairs. In some cases, individuals can be seen communicating with the person immediately behind them.

	
(a) Group 1 and 2.	(b) Group 3.



(c) Group 4.



(d) Group 5.

(e) Group 6.

Figure 129. Groups of workers being allowed into the external stairs.

5.1.3.2 Uncertainties in the building procedures

As the number of workers on the hanging deck is not known and the procedures for these workers can have a significant impact on the time to exit the jumpform, it was decided not to represent the middle hanging deck in the validation model. Apart from the workers on the upper deck (21 workers), all other workers (22 workers) are assumed to be located on the lower deck. By excluding the hanging deck, the predictions of the exiting process from the jumpform may be quicker than in reality as there are no workers initially located on the hanging deck within the model. The degree of uncertainty is dependent on the number of workers initially located on the hanging deck.

Regulating the flow on entry into the external hanging stairs was only approximate; the timing could not be precisely every 60 s. Furthermore, the bunching on the stairs and the movement of workers in groups results in workers regulating their speeds to remain in contact with each other. One way of addressing this behaviour is to ensure that all workers are given the same stair descent speed so that they remain in a relative group during their descent. It would also be reasonable to assign the group with a reduced stair descent speed to represent the bunching behaviour and self-imposed regulating of personal travel speeds.

5.1.4 Response time distribution

5.1.4.1 Specifying the response time distributions

The generalised response time distributions for the validation data-set are derived from the generalised response time curves presented in Section 4.6.1.4. These response time distributions are based on combining the response times from the various trials as explained in Section 4.6. These are the response time distribution for the ***HPFW*** (see Figure 90 from Section 4.6.1.4) defined by Equation 5 and the response time distribution for the ***MB*** (see Figure 94 from Section 4.6.2.3) defined by Equation 10.

These two response time distributions represent the response times of 60 workers in the formworks and 157 workers in the remainder of the building from three trials.

5.1.4.2 Uncertainties in the response time distributions

As noted in Section 5.1.2.1, there are 102 workers located on Level 3 and this level consists of the staff canteen, construction site offices, staff lockers and changing rooms. Response times for workers engaged in these types of activities were not captured by this project and so the activities of these workers cannot be represented reliably within the validation data-set. Response times could be allocated to these activities derived from other sources, but this would not result in an accurate indication of how the modelling represents construction site-specific activities. Thus, it was decided to exclude these from the validation analysis.

Another issue concerns the number of workers for which response time data was collected. In Trial 4 there were 43 workers in the formworks and 233 workers in the main building, excluding the 155 workers located on Level 1 to 3. However, in Trial 4 response times of only 82 workers were collected, including 38 workers in the formworks and 44 workers in the main building, i.e. not every worker's response time was collected and represented within the generalised response time distributions. While it is assumed that the generalised response time distributions used in the validation data-set may provide a comprehensive representation of the response times in general, this may not be a complete representation of the specific behaviour that occurred during Trial 4.

5.1.5 Exit curves

5.1.5.1 Specifying the exit curves

The validation data-set consists of two exit curves, one defining the exit times of the population from the building at the defined end point of the evacuation and the second one defining the exit times of workers from the jumpform.

As described in Section 5.1.4.2, the response times of the 102 workers involved in non-work-related activities on Level 3 were not collected. As a result, it is not appropriate to include these workers in the validation data-set. It was therefore decided to examine the evacuation performance of workers from the levels above Level 3 only. Excluding the workers from Levels 1 to 3 (155 workers; see Table 34) results in a total building population of 227 (also excluding the six supervisors in the jumpform). Furthermore, the end point for the analysis is the bottom of the flight of stairs that ends on Level 3. The evacuation time for each worker is defined as the time at which the worker's trailing leg leaves the last tread of the flight of stairs that ends on Level 3. This is prior to the worker exiting the gate on the landing of Level 3 (see Figure 123). The building exit curve for the validation analysis is depicted in Figure 130.

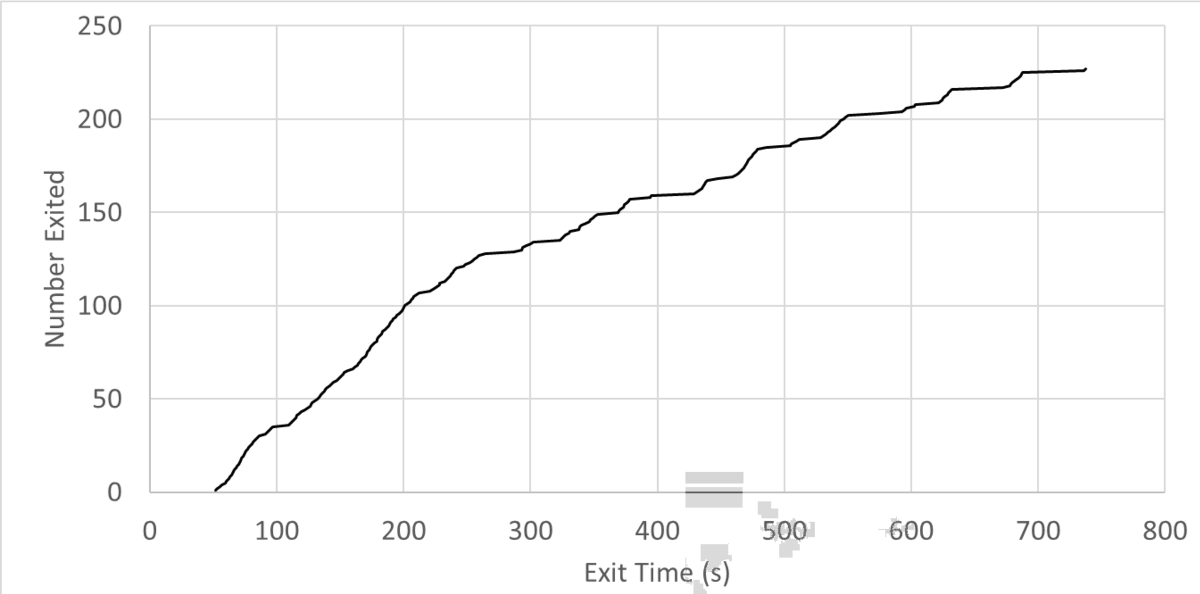


Figure 130. Building exit curve for the population defined as time of arrival at the bottom of the stairs on Level 3.

The jumpform exit curve is defined as the time at which workers exit the jumpform (see Figure 131). The time that workers exit the jumpform, i.e. entering the hanging stair on the top deck, is defined as the time at which the worker first steps onto the top step of the hanging stairs.

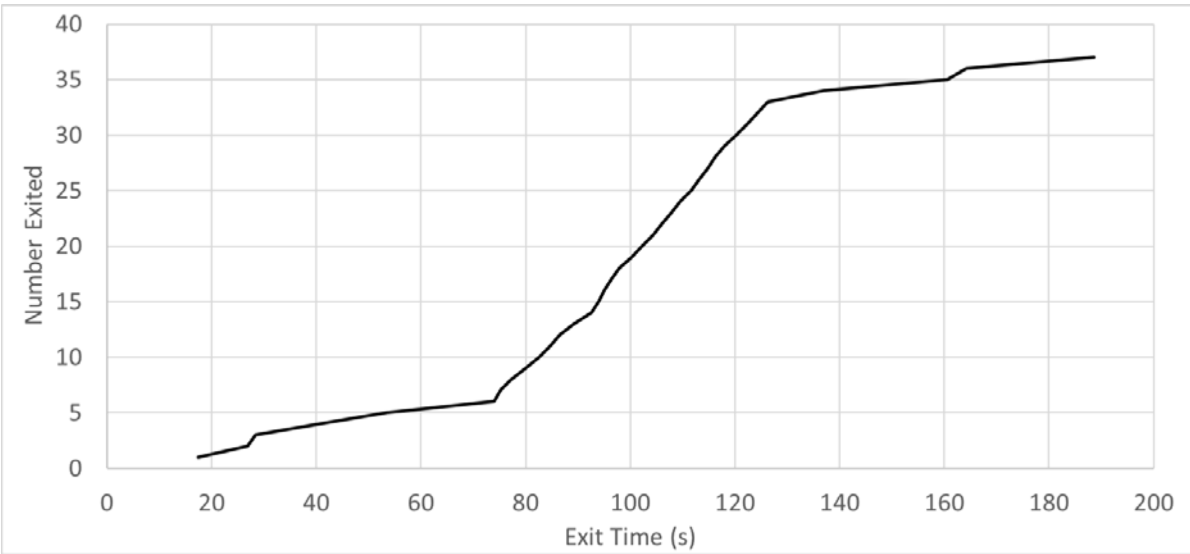


Figure 131. Jumpform exit curve defined as time at which each worker steps onto the top step of the hanging stairs.

Key Finding 9.1: Validation data-set – A validation data-set has been defined describing the evacuation of a high-rise construction site. The validation data-set incorporates:

- ***a building geometry of 33 levels above ground (with the formworks located at Level 33 and the top of the jumpform at Level 34)***
- ***the jumpform involving 37 workers***
- ***the main building involving 190 workers***
- ***floor surfaces consisting of concrete, decking and decking with rebar***
- ***temporary scaffold stairs and ladders***

- ***specified response time distributions for the jumpform and main building***
- ***specified starting floor locations for 100 workers***
- ***exit curves for the jumpform and main building.***

Uncertainties in the data-set include:

- ***location of obstacles and blockages on the floors excluding the jumpform***
- ***incomplete description of starting floor location for 127 workers***
- ***incomplete specification of worker response times.***

5.2 A performance metric to assess quality of model predictions

Along with the validation data-set, it is desirable to specify objective performance measures of the level of agreement between the predicted data and the measured data rather than simply rely on subjective assessments. This is particularly important if the validation analysis is to be used in regulatory applications. Based on the work of Peacock et al [95], the authors have defined a performance metric along with acceptance criteria that could be used to assess how well maritime evacuation model predictions agreed with a set of experimentally based validation evacuation curves [96]. It is suggested that this metric could also be used to assess how well building evacuation models predict exit curves for building structures.

Before presenting the formulation of the metrics it is necessary to introduce some terminology. The series of measured experimental data is represented by the n-dimensional vector E = (E_1, …. E_n), where E_i represents the measured evacuation time for the i_{th} worker. Similarly, the series of predicted data is represented by the vector m = (m_1, …. m_n), where m_i represents the predicted evacuation time for the i_{th} agent. The metric used to quantify the level of agreement between predicted and measured values consists of three measures (see Equations 11 to 13).

$$\frac{\|E-m\|}{\|E\|}=\frac{\sqrt{\sum_{i=1}^{n}(E_i-m_i)^2}}{\sqrt{\sum_{i=1}^{n}E_i^2}} \quad \textbf{(11)}$$

$$\frac{\langle E,m\rangle}{\|m\|^2}=\frac{\sum_{i=1}^{n}E_i m_i}{\sum_{i=1}^{n}m_i^2} \quad \textbf{(12)}$$

$$\frac{\langle E,m\rangle}{\|E\|\|m\|}=\frac{\sum_{i=s+1}^{n}\frac{(E_i-E_{i-s})(m_i-m_{i-s})}{s^2(t_i-t_{i-1})}}{\sqrt{\sum_{i=s+1}^{n}\frac{(E_i-E_{i-s})^2}{s^2(t_i-t_{i-1})}\sum_{i=s+1}^{n}\frac{(m_i-m_{i-s})^2}{s^2(t_i-t_{i-1})}}} \quad \textbf{(13)}$$

The first is the Euclidean Relative Difference (ERD) defined by Equation 11. This is used to assess the average difference between the experimental data (E_i) and the model data (m_i), i.e. the overall agreement between the two curves. This equation should return a value of 0 if the two curves are identical in magnitude. The smaller the value for the ERD, the better the overall agreement. An ERD of 0.2 suggests that the average difference between the model and experimental data points, taking into account all the data points, is 20%.

The second measure is the Euclidean Projection Coefficient (EPC) defined by Equation 12. The EPC calculates a factor which, when multiplied by each model data point (m_i), reduces the distance between the model (m) and experimental (E) vectors to its minimum. Thus, the EPC provides a measure of the best possible level of agreement between the model (m) and experimental (E) curves. An EPC of 1.0 suggests that the difference between the model (m) and experimental (E) vectors are as small as possible.

The third measure is the Secant Cosine (SC) defined by Equation 13. Unlike the other two measures, it provides a measure of how well the shape of the model data curve matches that of the experimental data curve. It makes use of the secants (which approximate to tangents) through both curves. An SC of 1.0 suggests that the shape of the model (m) curve is identical to that of the experimental (E) curve.

The *t* in Equation 13 is a measure of the spacing of the data. For the evacuation data representing the exit curves the spacing of the data is 1, i.e. there is a data point for each worker/agent that exits the building. Thus, the difference in *t* consecutive values in Equation 13 is 1.

The *s* in Equation 13 is a factor that represents the period of noise in the data, or variations in the experimental data resulting from microscopic behaviour not possible to reproduce in the model. Selecting a value of *s* which is greater than the period of the noise in the data provides a means to smooth out the effect of the noise. However, care must be taken in selecting the value of *s*. If *s* is too large, the natural variation in the data may be lost, while if *s* is too small, the variation in the data created by noise may dominate the analysis. Selecting an appropriate value of *s* is dependent on the number of data points in the data-set, given by *n*. It is therefore desirable to keep the ratio *s/n* as low as possible.

For data-sets in which an experimental and model data point are available for each person, if the ERD = 0.0, then it would not be necessary to consider the other measures as the two data-sets would be identical. In all other cases it is necessary to consider the three measures together in order to get a good indication of how well the two data-sets match each other. As the model data curve can cross the experimental data curve one or multiple times, the EPC can return a value close to 1.0 while there is a difference between the two curves. Similarly, the SC can return a value of 1.0 even though the model and experimental data curves are offset by a constant value. In general, for the model and experimental curves to be considered a perfect match, it is necessary to have all three measures at their optimal values, i.e. ERD = 0.0, EPC = 1.0 and SC = 1.0.

If the evacuation trials were repeated, it is highly unlikely the exact same exit curve would be produced, even if the starting conditions were all the same (i.e. same workers in the same location doing the same tasks). Thus, each evacuation trial would produce a different exit curve and different total evacuation time. As Trial 4 was the only trial conducted at this construction site at this height, it is not known where the actual trial curve lies on the distribution of all possible evacuation curves. Does the actual Trial 4 result represent the fastest evacuation or the slowest evacuation or somewhere in between? As it is not known how representative the trial result is of the likely distribution of trial results, a distribution of simulation results should be produced, and the simulation run which most closely matches the actual evacuation trial should be used to assess the performance of the evacuation modelling software tool.

The simulation producing the smallest ERD is selected to be the suitable representative from the group of simulation results to compare with the experimental result.

In the previous application of this methodology [96] the following set of pass/fail acceptance criteria were used to assess how well the model predictions agree with the experimental data:

- **(i) ERD ≤ 0.25**
- **(ii) 0.8 ≤ EPC ≤ 1.2**
- **(iii) SC ≥ 0.8 with s/n = 0.03**
- **(iv) Predicted total evacuation time for the overall evacuation to be within 15% of the measured value.**

These particular acceptance criteria were selected for two primary reasons. First, there were considerable uncertainties in the validation data-set. This was not only related to the starting location of the passengers, but also the number of passengers that actively took part in the trial – not everyone present actually actively participated in the evacuation. Also, response times were not collected for all the participants. These uncertainties in the validation data-set require a certain degree of tolerance in the interpretation of the level of agreement between the model predictions and the experimental data. The second issue concerned tuning the acceptance criteria around the performance of three different maritime evacuation models. Three different evacuation models were utilised in the assessment; these models were considered to be the leading maritime evacuation models available at the time of the assessment. Each of these models was considered by maritime authorities to be acceptable to use in analysis of passenger ship evacuation and so should be able to pass the acceptance criteria. To ensure a level playing field between these three models, and other models that may wish to use the validation data-set and the acceptance criteria, the pass/fail criteria were selected to ensure that these three models would pass and hence be acceptable. Thus, other models that undertook the test and met the pass criteria would be assessed to be as good as the three leading maritime evacuation models. Clearly, the level at which a model passes could be used to argue that the model was better or worse than the performance of the leading models, in this evaluation.

While it is not suggested that this specific set of criteria should be used for the evaluation of building evacuation models for the construction site validation case, it provides, at the very least, a starting point to the definition of a set of acceptance criteria.

As highlighted in this section, the suggested construction site validation data-set has a number of uncertainties which should allow some leniency in the interpretation of what is considered acceptable.

Finding 9.1: Specification of a performance metric – A performance metric has been defined to objectively describe the goodness of fit between model predictions and experimental data. The performance metric makes use of three measures:

- ***Euclidean Relative Difference (ERD) – which assesses the average difference between the experimental data and the model predicted data***
- ***Euclidean Projection Coefficient (EPC) – which provides a measure of the best possible level of agreement between the model predictions and experimental curves that can be achieved by scaling the model predictions by the EPC***
- ***Secant Cosine (SC) – which provides a measure of how well the shape of the model predicted data curve matches that of the experimental data curve.***

The approach enables uncertainties in the validation data-set to be taken into consideration by identifying acceptable values for each of the parameters.

5.3 The evacuation software

5.3.1 Introduction to buildingEXODUS

The software used in this analysis is buildingEXODUS [29–31]. This is an agent-based evacuation model [27, 28] which utilises a rule-base to represent the evacuation behaviours of individuals. The EXODUS software takes into consideration people-people, people-fire and people-structure interactions. It comprises five core interacting sub-models: the OCCUPANTS, MOVEMENT, BEHAVIOUR, TOXICITY and HAZARD sub-models. The OCCUPANTS sub-model describes an individual as a collection of defining attributes and variables such as name, gender, age, maximum unhindered fast walking speed, maximum unhindered walking speed, response time and agility. The HAZARD sub-model controls the atmospheric and physical environment by importing the fire data, like those generated by the SMARTFIRE CFD fire model. The TOXICITY sub-model determines the physiological effects on an individual exposed to the toxic and thermal environment distributed by the HAZARD sub-model. This is determined using the Fractional Effective Dose (FED) and Fractional Irritant Concentration (FIC) concept [97]. Within buildingEXODUS two models are provided for the determination of the fractional effective dose of radiative heat, the so-called Pain Threshold model (in which the dose required to cause effect (Dr) is 80 $s(kW/m^2)^{4/3}$, which is the equivalent to an exposure of 2.5 kW/m^2 for 24 s) and the Incapacitation model (in which Dr = 1,000 $s(kW/m^2)^{4/3}$, the equivalent to an exposure to 2.6 kW/m^2 for 5 minutes which can result in a 1% mortality) [98]. The Incapacitation model is used in the calculations in this study. When an occupant moves through a smoke-filled environment their travel speed is reduced according to the experimental data of Jin [99] which relates light extinction coefficient to walking speed. All these effects are communicated to the BEHAVIOUR sub-model which, in turn, feeds through to the movement of the individual. The behaviours in buildingEXODUS include crawling, climbing over seats, maintaining target exits, wayfinding, etc.

An agent is considered incapacitated when the FED (either FIN or FIH) is equal to one. An agent is considered injured if their FED (either or both FIH or FIN) is greater than 0.1. The HAZARD sub-model of buildingEXODUS can read data generated by the SMARTFIRE CFD fire model. To transfer CFD fire hazard data the user must define a consistent set of zones within both the SMARTFIRE and EXODUS geometry. These zones are intended to represent regions in which the fire hazard data is expected to be near uniform, i.e. exhibiting small spatial variation. The hazard data within SMARTFIRE is averaged over these zones to produce two values, a hazard value at a nominal head height and a value at a nominal knee height. Some applications of this coupled fire and evacuation simulation technique can be found in [98, 100, 101].

5.3.2 buildingEXODUS calibration and setup

The buildingEXODUS software was calibrated to represent the validation data-set configuration as described in Section 5.1 and more generally the movement data presented in Sections 4.7 and 4.8. In addition, the software was modified to enable the specification of different types of floor surfaces and stair types.

More specifically, the calibration involved:

- **population distribution:** this involved specifying the location of all 382 agents. The uncertainty in population location associated with Levels 4–6, Levels 9–17 and Levels 28–32 (see Table 34 in Section 5.1.2) was dealt with by randomly distributing the appropriate number of agents between the specified floors
- **response times:** specifying the appropriate response time distributions for the validation analysis. This consisted of two response time distributions:
    - for the formworks the high-priority response time distribution specified in Equation 5 (see Section 4.6.1.4) was used

    - for the main building the response time distribution specified in Equation 10 (see Section 4.6.2.3) was used
- **procedures:** specifying the regulated flow of the formworks workers onto the temporary stair on Level 28 of approximately six people/min (see Section 5.1.3). This was achieved by assigning an internal door at the entrance of the hanging stairs on Level 28 with a repeated sequence of specified door opening/closing times. The door remains closed for 55 s and is then opened for 5 s, allowing an average of six people through at a time
- **stair speeds:** on regular stairs the model assumed the default buildingEXODUS stairs speeds. On the temporary stairs and ladders, buildingEXODUS used the speeds derived from the trials and presented in Table 31 and Table 32 in Section 4.8.2
- **stair usage:** the minimum spacing between agents on temporary dogleg stairs identified in Section 4.7 was used, i.e. two stair treads
- **speeds on different walking surfaces:** on concrete surfaces, the standard flat buildingEXODUS walking speeds were used. To represent the walking speeds on different types of surfaces, the reduction factors presented in Table 27 in Section 4.8.1 were used
- **geometry:** the building geometry as presented in Figure 122 was used within buildingEXODUS. Note that on all the floors with the exception of the jumpform no clutter is represented. The clutter introduced into the jumpform is intended to be representative of the clutter in the jumpform, but is not an exact reproduction of the clutter. Presented in Figure 132 are images depicting the building within the buildingEXODUS software.

Modifications to the standard buildingEXODUS software included:
- **floor surfaces:** new node types were introduced to represent different types of floor surface, i.e. decking and decking with rebar. Associated with each floor surface was a travel speed reduction factor (user specified) appropriate for the floor surface. The reduction factor together with the agent allocated walking speed on the flat would produce the walking speed on the specific surface
- **stair types:** new transit nodes were introduced to represent the new types of temporary scaffold stairs (dogleg and parallel) and ladders. A standard parameter used in buildingEXODUS stair definition is the minimum spacing between agents on stairs. For standard stairs, the minimum spacing is one tread, i.e. agents attempt to keep one tread between themselves and the agent in front. Using this parameter, it is possible to specify the reduced packing density for temporary dogleg scaffold stairs observed in the trials. On ladders only a single agent was permitted to occupy the ladder at any one time
- **travel speeds:** population attributes were expanded to include ascent and descent speeds on the new stair types.

Finding 9.2: Calibration of evacuation software tool to simulate construction site evacuation – The buildingEXODUS software was calibrated to represent the validation data-set configuration as described and more generally the movement and response time data-sets. In addition, the software was modified to enable the specification of different types of floor surfaces and stair types.

Finally, the end point for the simulation was defined as the landing at the base of the flight of stairs on Level 3. Agents were deemed to have ‘exited’ as they stepped off the last stair tread on Level 3, prior to exiting through the gate at the bottom of the stairs on Level 3. However, it is noted that the entire building was modelled, including the gate exit point from Level 3, the stairs all the way to the ground level, and all the workers from Level 3 down to the ground Level. While these agents are not part of the validation data-set, it is important that they are represented as their presence may cause congestion at the stair on Level 3, effectively delaying the ‘exit’ of the workers descending from higher up. Similarly, the restricted exit point caused by the gate at the base of Level 3 is also represented within the model. The workers located on Levels 1 to 3 are given response times from the generalised distribution.

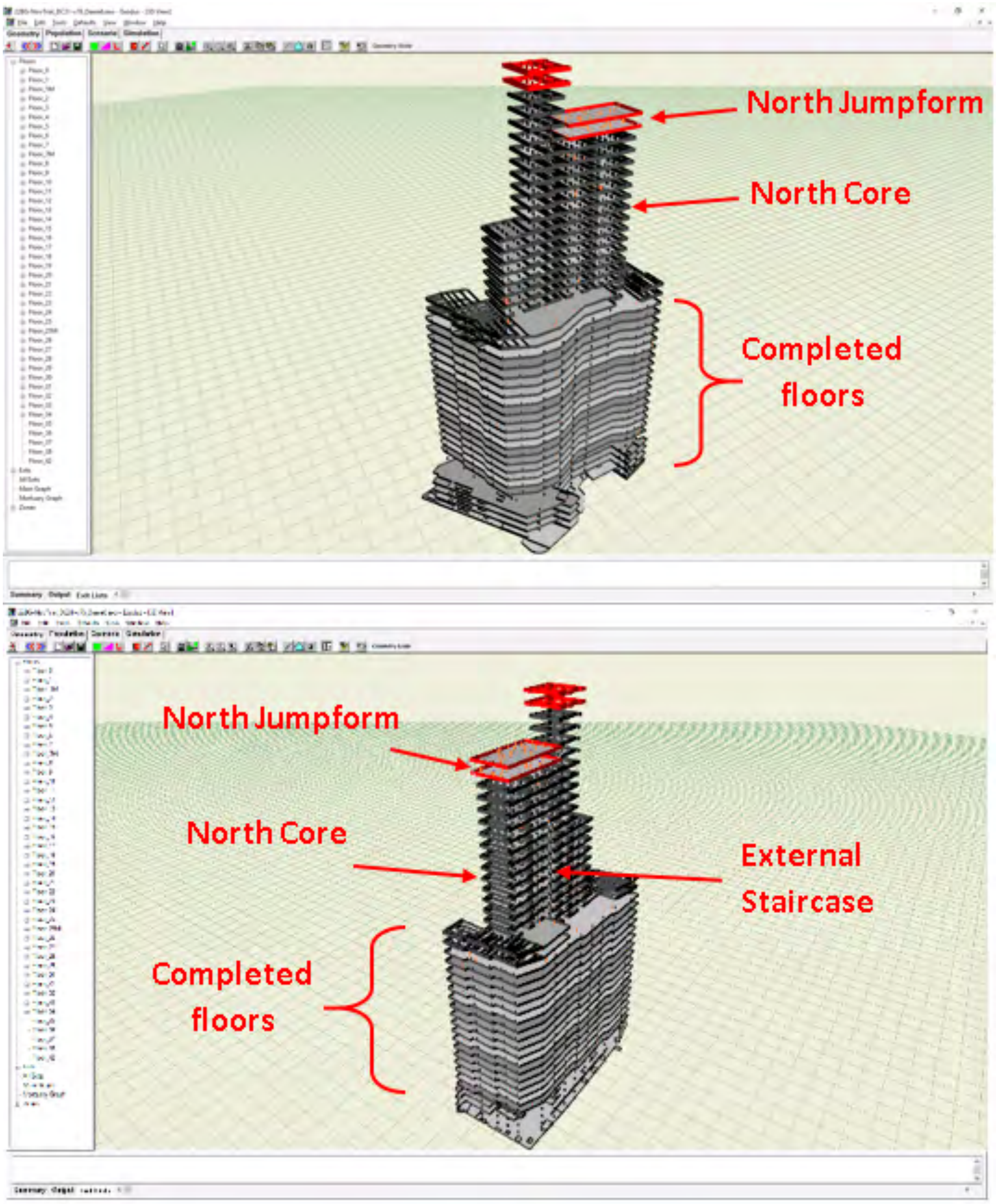


Figure 132. buildingEXODUS representation of the validation case building geometry based on 22 BG.

5.4 The buildingEXODUS results for the validation scenario

As buildingEXODUS is a stochastic evacuation simulation software tool, the software must be run a number of times in order to generate a range of possible simulation outcomes. Furthermore, it is necessary to randomise the starting location of the agents to accommodate uncertainties in starting floor location, starting location on a known floor and floor clutter. For the purposes of this validation exercise the software was run 100 times, with the population being deleted and repopulated after every simulation run. In this way, each simulation had a different population distribution and each agent had a different response time, albeit within the parameters specified in Section 5.3.2.

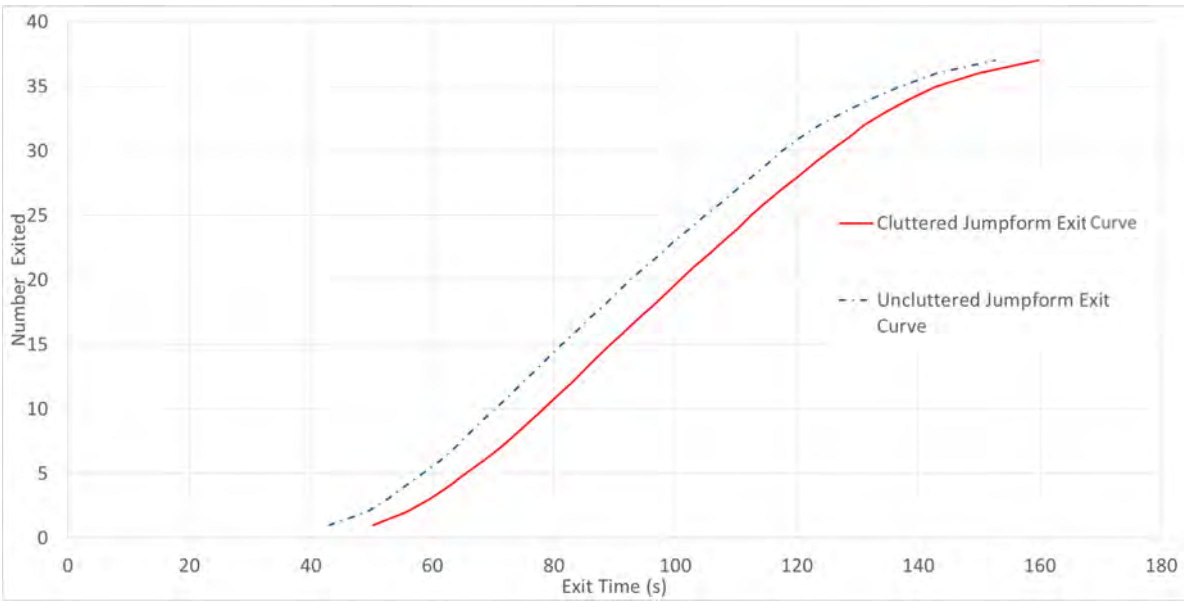
The subjective performance of the software in undertaking the validation analysis is presented in Section 5.4.1, while the objective performance of the software using the performance metric is presented in Section 5.4.2.

5.4.1 The generalised validation analysis

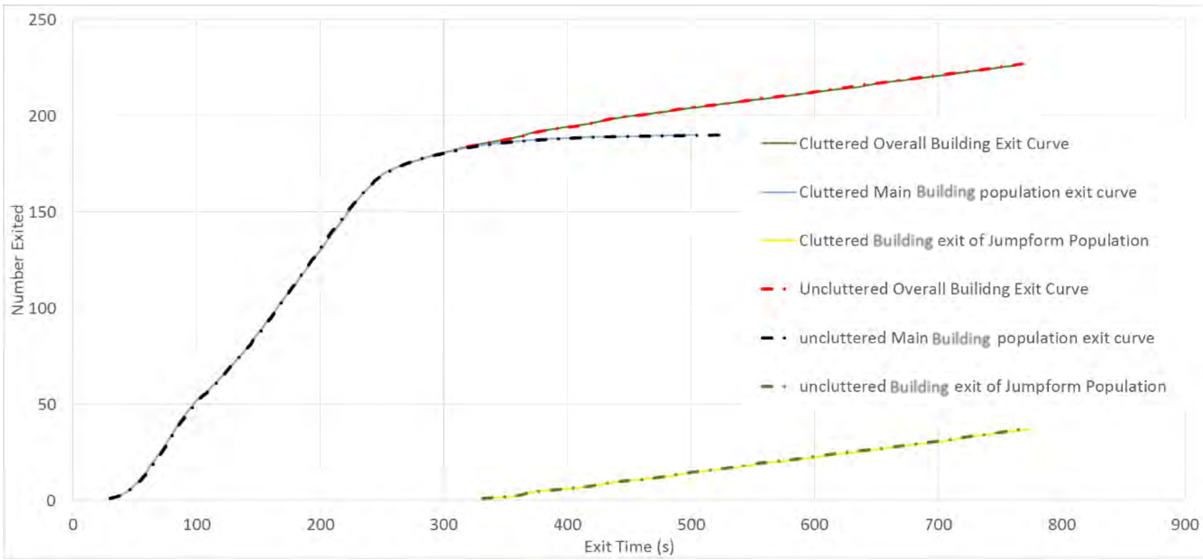
The validation analysis makes use of the generalised response time distributions. As part of this analysis an assessment of how the presence of the clutter in the jumpform (see Figure 127) influences the evacuation performance was undertaken. Unless stated otherwise, the exit curves predicted by the model represent the average exit time for each agent based on 100 unique simulations.

5.4.1.1 Impact of clutter in the jumpform

Presented in Figure 133 are the curves for exiting from the jumpform (Figure 133a) and exiting from the entire building (Figure 133b). As can be seen, the presence of clutter has an impact on the exiting time for the jumpform, extending the overall average clearance time from 153 s to 160 s, an increase of 7 s or about 5%. This increase in average exit time is consistent, being a similar absolute increase in exiting time for the first, middle and last worker to exit from the jumpform. Thus, the presence of clutter has an impact on the time to clear the jumpform. This is expected as the level of clutter within the jumpform is severe, resulting in an increase in the average travel distance for agents to exit the jumpform. For example, an agent located on the upper deck and at an extreme corner of the jumpform has their travel distance (measured from their starting location to the ladder exit point) increased from 30.8 m to 34.9 m, an increase of 13%. For reference, the travel distance in a direct line would be 28.6 m. It is expected that the impact of clutter on the larger floor plates of completed or near completed floors will be more significant as the workers will have a much longer distance to walk on average.



(a) The exit curves for the jumpform.



(b) The exit curves for the entire building.

Figure 133. The buildingEXODUS predicted average curves produced for scenarios involving clutter and no clutter in the jumpform for (a) exiting the jumpform and (b) exiting the entire building.

Presented in Figure 133b are the curves for exiting the building for the entire building population, the main building population and the jumpform population with and without clutter within the jumpform. As can be seen there is no difference in building exiting times for the cluttered and uncluttered cases, even for the jumpform workers. This is expected as the clutter is only present in the jumpform and so will only impact jumpform workers, and the distance travelled by the jumpform workers to exit the building after they have exited the jumpform is much greater than the distance they must travel to exit the jumpform. Thus, any impact of clutter on exiting times is swamped by the more significant times incurred in exiting the building.

Nevertheless, if clutter was represented within the model on each floor, it is expected that this would have a more significant impact on exiting times, shifting the predicted building exit curve towards longer exiting times (towards the right). As the actual clutter present during the evacuation drill was not recorded and hence not included in the model; this will need to be taken into consideration when judging how close the model predictions are to the experimental data.

5.4.1.2 The generalised validation

For the remainder of the validation test cases, the cluttered jumpform configuration is used. Presented in Figure 134 is a predicted exit curve produced by a single simulation of buildingEXODUS, with a total evacuation time equivalent to the average predicted total evacuation time (from 100 repeated simulations). The overall shape of the predicted exit curve for the entire building generally follows that of the experimental exit curve. In particular, it is noted that the tail of the predicted and measured overall exit curves have a number of small fluctuations. This is due to the behaviour of the workers from the jumpform who were controlled by the supervisor on Level 28 who regulated the flow onto the temporary stairs in batches of six workers per every 60 s (approximately).

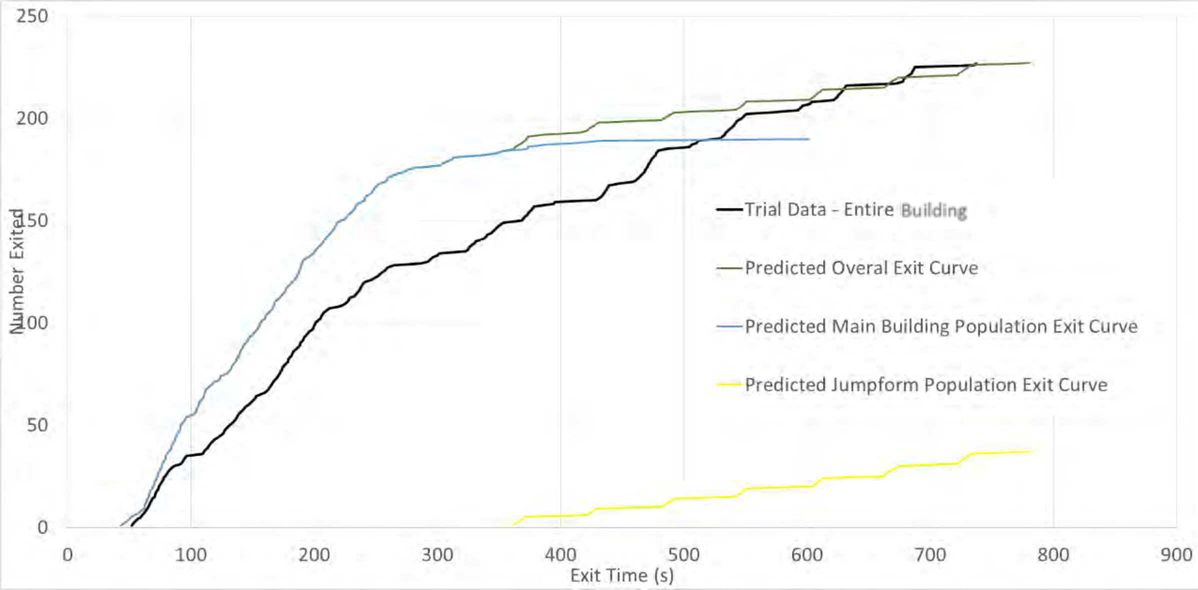


Figure 134. The buildingEXODUS predicted curves produced by a single simulation and the experimental curve.

As can be seen in Figure 134, there is a significant overlap between the exit curves for the main building population and the jumpform population – from 362 s to 602 s. However, in this span of 240 s only three workers from the main building exit. These are the three workers initially located on Levels 28–32 (see Table 34). As these workers are located above Level 28, they must descend the hanging stairs down to Level 28. Once on Level 28, they then join the jumpform workers and enter the temporary stairs, which start on Level 28. As a result, these three workers are also caught up in the gate process on Level 28. In the simulation depicted in Figure 134, these three main building workers manage to exit the building reasonably quickly, but over the 100 repeated simulations they can be significantly delayed through a combination of long response times, initial level location and missing one or two gate cycles due to queuing at the gate. For instance, the time for the last worker from the main part of the building to exit varies from 336 s to 791 s (see Table 35).

Table 35. Exit times of the last three workers from the main building derived from the 100 repeated simulations.

	3rd last	2nd last	last
Max exit time (s)	480.9	786.1	791.4
Average exit time (s)	383.2	424.3	504.4
Min exit time (s)	304.4	316.6	335.9

For the case presented in Figure 134, the difference in predicted (single simulation in which the total evacuation time is close to the average predicted total evacuation time) and measured times for the first worker to exit, the 113th to exit (representing 50^{th} percentile of the population) and 90th percentile, 95th percentile, 97th percentile, 99th percentile exit times and the total evacuation time are presented in Table 36. For the last 10% of the workers to exit the building (all from the jumpform), the predicted evacuation time varies from an under-prediction of 9% to an over-prediction of 6%. The exit times for these individuals are dictated by the operation of the gate on Level 28 and the model appears to do a reasonable job of predicting their corresponding exit times. However, the time for the 50th percentile exit is under-predicted by 25%.

Table 36. Difference in predicted and measured exit times.

	1st	50% (113)	90% (204)	95% (216)	97% (220)	99% (225)	100% (227)
Experimental exit times (s)	51.9	232	593	632	680	687	737
Predicted exit time (s)	43.2	173	542	664	674	731	781
% Diff	-17%	-25%	-9%	5%	-1%	6%	6%

There are several potential reasons to account for the under-prediction of the 50th percentile exit time. The first relates to the nature of the response time distribution used to represent the response time for the bulk of the building. The generalised response time distribution was used in this case and not the precise response time from the actual trial. Furthermore, the generalised response time distribution for the main building was based on 182 data points collected from three trials, including 44 data points from Trial 4. This may be insufficient to represent the response behaviours of the 190 workers in the main building during Trial 4.

Secondly, as already mentioned, the clutter has not been represented on all the floors below the jumpform. This could have a significant impact, especially on the larger completed or partially completed floors. The presence of clutter in the smaller floor area of the jumpform delayed the time for workers to exit the jumpform by approximately 5% (or 7 s). On the larger area of the main floors, the delay could be expected to be significantly longer than this. As clutter is expected to increase the time required by each worker to exit a floor below the jumpform, the exit curve for the main part of the building would be effectively shifting to the right and closer to the trial curve.

Thirdly, the locations of some of the workers above Level 3 is unknown as indicated in Table 34. There are 75 workers located between Levels 4 and 6, 49 workers located between Levels 9 and 17 and three workers located between Levels 28 and 32. In total, the location of 127 of the 190 workers in the main building is not known precisely. In the simulation presented in Figure 134, the location of these 127 workers is randomly distributed between these specified ranges of floors. However, if these 127 workers were positioned on the upper floors within the ranges, the predicted exit curve for the main building population would be shifted to the right and closer to the trial curve.

Finally, there is a considerable amount of variation within each repeated simulation in terms of precise starting location on a floor, floor location for the workers with uncertain floor starting location, and response time from the prescribed response time distribution. These variations can produce a large spread in exit times for each worker. Presented in Figure 135 is the window of possible exit curves produced by the 100 simulations.

The window is created by taking the minimum and maximum predicted evacuation time for each worker. Also shown in the figure are the average predicted exit curve and the experimental curve. As can be seen, with the exception of the total evacuation time, the predicted maximum exit times are significantly closer to the trial curve than the average or minimum predicted exit times. Thus, the difference between the predicted and measured exit curves is dependent on which of the 100 repeated simulations is used to make the comparison.

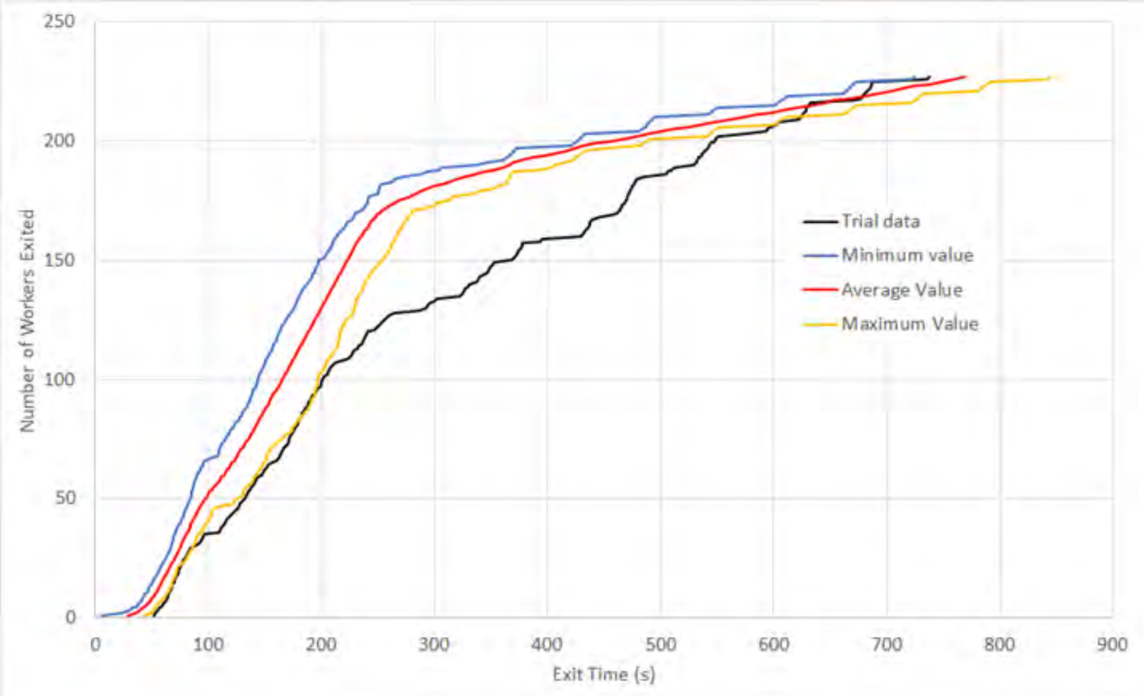


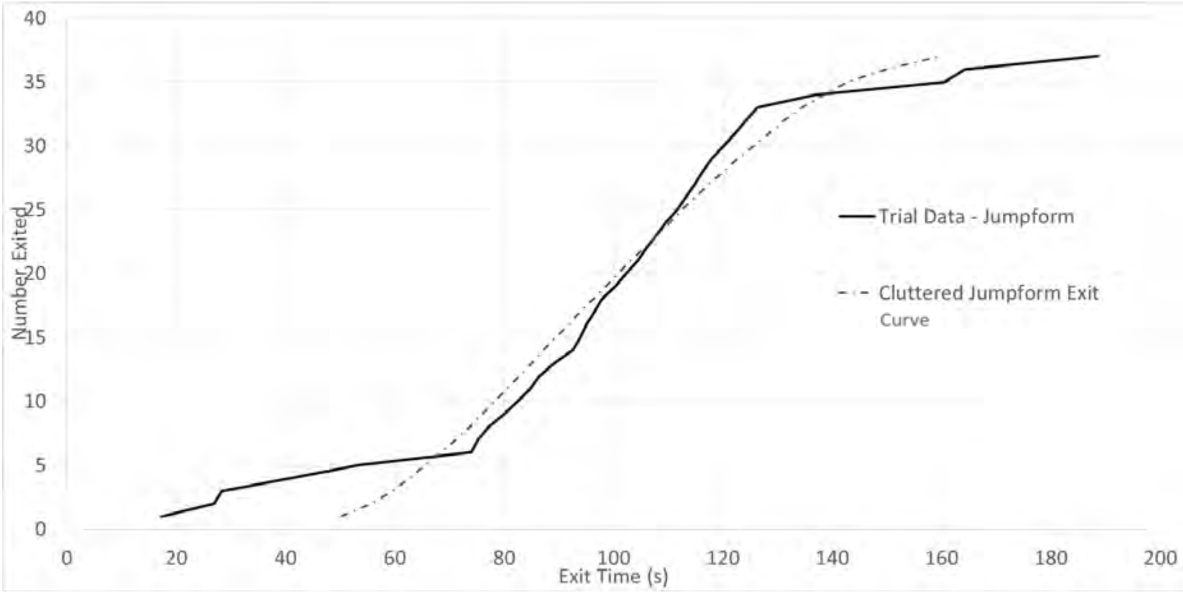
Figure 135. The buildingEXODUS predicted window of exit curves generated from 100 repeated simulations along with the experimental curve.

Presented in Table 37 is a comparison of the minimum and maximum predicted exit times with the experimental exit times for the first worker to exit, the 113th to exit (representing 50th percentile of the population), the 90th percentile, 95th percentile, 97th percentile, 99th percentile exit times and the total evacuation time. As can be seen, with the exception of the total evacuation time, the maximum predicted exit times produce a reasonably close approximation to the trial times. For the last 10% of the workers to exit the building (all from the jumpform), the maximum predicted evacuation time varies from an under-prediction of 8% to an over-prediction of 15%. The exit times for these individuals are dictated by the operation of the gate on Level 28 and the model appears to do a reasonable job of predicting their corresponding exit times. However, the time for the 50th percentile exit is under-predicted by only 8%. Overall, the maximum predicted exit curve produces better agreement with most of the trial data, but over-predicts the total evacuation time by about 14%.

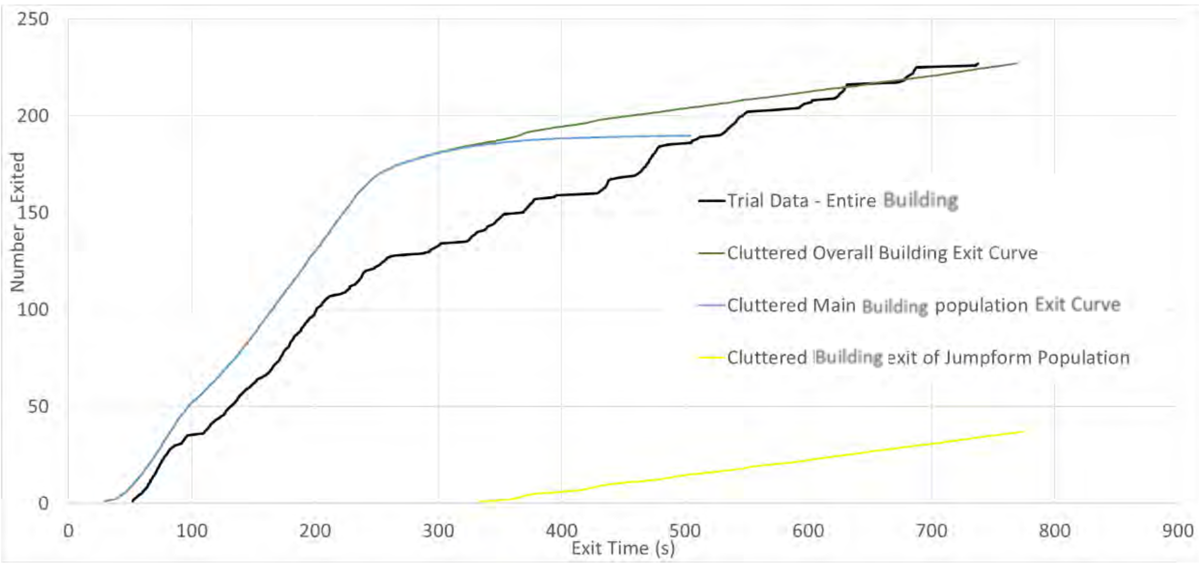
Table 37. Difference in predicted minimum and maximum exit times and measured exit times.

	1st	50% (113)	90% (204)	95% (216)	97% (220)	99% (225)	100% (227)
Experimental exit times (s)	51.9	232	593	632	680	687	737
Min predicted exit time (s)	6.2	156	481	604	662	673	724
Max predicted exit time (s)	43	213	546	722	732	791	844
% Diff ((Max-Trial)/Trial)	-17%	-8%	-8%	14%	8%	15%	14%

As can be seen in Figure 135 there are considerable variations in the predicted exit curves. To compare with the experimental curve we take the average exit curve as a representative model prediction. This is determined by taking the average time for each person to exit from the 100 repeated simulations. Presented in Figure 136 are the average predicted exit curves for the jumpform (Figure 136a) and the entire building (Figure 136b) compared with the experimental curves. We note that the average predicted time to clear the jumpform was 160 s compared with 189 s in the trial, an under-prediction of 15%. Similarly, the average predicted time to clear the building was 769 s compared with 737 s in the trial, an over-prediction of 4%.



(a) The exit curves for the jumpform.



(b) The exit curves for the entire building.

Figure 136. The average buildingEXODUS predicted exit curves along with the experimental curve.

The general shape of the average curve is similar to that shown in Figure 134; however, the data is smoothed out (due to representing the average) and so details such as the fluctuations in the tail are lost.

For the average curve, the difference in predicted and measured times for the first worker to exit, the 113th to exit (representing 50th percentile of the population) and 90th percentile, 95th percentile, 97th percentile, 99th percentile and the total evacuation time are presented in Table 38. For the last 10% of the workers to exit the building (all from the jumpform), the predicted evacuation time varies from an under-prediction of 16% to an over-prediction of 9%. The exit times for these individuals are dictated by the operation of the gate on Level 28, and the model appears to do a reasonable job of predicting their corresponding exit times. However, the time for the 50th percentile exit is under-predicted by 22%.

Table 38. Difference in predicted (average curve) and measured exit times.

	1st	50% (113)	90% (204)	95% (216)	97% (220)	99% (225)	100% (227)
Experimental exit times (s)	51.9	232	593	632	680	687	737
Predicted exit time (s)	29.4	180	500	645	692	748	769
% Diff	-43%	-22%	-16%	2%	2%	9%	4%

Keeping in mind the uncertainties in the experimental data (uncertain starting location for some workers, a lack of representation of clutter on the floors and an incomplete representation of the response time distribution), the level of agreement is considered reasonable. In the next section we make use of the validation metric to determine a more objective assessment of the degree of agreement between the model predictions and the experimental data.

Key Finding 9.2: Subjective performance of buildingEXODUS in validation scenario – The average exit curve produced by 100 repeated simulations of buildingEXODUS produces a reasonable approximation of the validation data-set. On average, the total evacuation time is over-predicted by 4% while the time for half the population to exit the building is under-predicted by 22%. The average time to clear the jumpform is under-predicted by 15%. Given the uncertainties in the validation data-set, this is considered an acceptable level of agreement.

5.4.2 Analysis of the evacuation software prediction using the performance metric

The three parameters associated with the performance metric are defined by Equations 11–13 and consist of the ERD, the EPC and SC (see Section 5.2). For each of the 100 repeated simulations the three parameters are calculated and the simulation producing the smallest ERD is selected as being the best prediction to represent the performance of the simulation.

Presented in Table 39 are a set of metric values for a sample of the repeat simulations. The sample includes the case with the largest ERD (0.29) and the smallest ERD (0.22). As there is not a large difference between the ERD values, this suggests that all 100 simulations produce curves with similar absolute differences between the predicted and measured data, with the average difference between the predicted and measured values over the 100 repeated simulations varying from 22% to 29%.

In determining the SC value an appropriate value for the ratio *s/n* must be selected. This represents an appropriate value by which noise is filtered out of the experimental data. From the experimental curve presented in Figure 136b, bumps in the curve can involve 16 workers. To remove the influence of these bumps, an *s/n* value of 0.07 would be appropriate. Thus, an *s/n* of 0.07 represents 7% of the data-set and implies *s* = 16 for this data-set. As a result, for the 227-point data-set, the gradients used in the evaluation of Equation 13 are spread over 16 data points. Based on this approach, the values for the metric for the buildingEXODUS simulation producing the smallest ERD are:

(i) ERD = 0.22
(ii) EPC = 1.13
(iii) SC = 0.82 with s/n = 0.07
(iv) Predicted total evacuation time for the entire building (797 s) is over-predicted by 8%.

These values suggest that the model does a reasonable job in predicting the overall evacuation. Presented in Figure 137 are the predicted exit curves for the jumpform (Figure 137a) and the entire building (Figure 137b) of the simulation case which produces the smallest overall ERD compared with the experimental data. The predicted time to clear the jumpform was 164 s compared with 189 s in the trial, an under-prediction of 13%. Similarly, the predicted time to clear the building was 797 s compared with 737 s in the trial, an over-prediction of 8%. As can be seen from Figure 137b, in some places, the predicted exiting times are smaller than the measured values (hence the relatively large value of ERD (0.22)); however, the general shape of the predicted exit curve is a reasonable approximation to the experimental curve (hence the value of SC (0.82) being reasonably close to 1.0), and in general, the overall difference could be minimised if all the exit times could be increased slightly (hence the EPC value (1.13) being larger than 1.0 and close to 1.0).

Table 39. Performance metric values for the overall exit curve derived from a sample of the 100 repeated simulations of the validation data-set including the smallest and largest ERD.

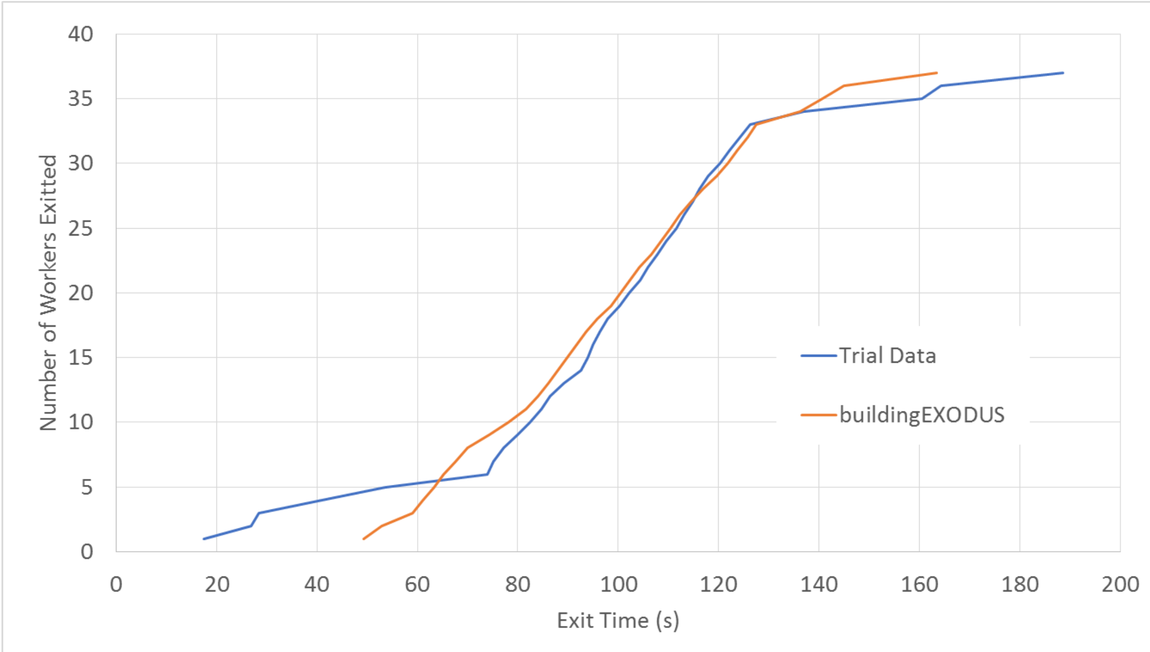
Simulation	ERD	EPC	n	s/n									
				0.01	**0.02**	**0.03**	**0.04**	**0.05**	**0.06**	**0.07**	**0.08**	**0.09**	**0.1**
ADL.sim	0.25	1.11	227	0.44	0.71	0.76	0.79	0.81	0.82	0.82	0.82	0.82	0.83
ADN.sim	0.25	1.16	227	0.51	0.70	0.77	0.79	0.80	0.81	0.81	0.81	0.82	0.82
ADO.sim	0.29	1.19	227	0.47	0.65	0.71	0.74	0.75	0.77	0.77	0.78	0.79	0.79
ADP.sim	0.23	1.10	227	0.35	0.66	0.72	0.75	0.78	0.79	0.80	0.81	0.81	0.82
ADQ.sim	0.25	1.15	227	0.52	0.70	0.76	0.78	0.79	0.80	0.80	0.81	0.81	0.81
ADR.sim	0.26	1.17	227	0.48	0.68	0.75	0.78	0.78	0.79	0.79	0.80	0.80	0.81
ADS.sim	0.26	1.15	227	0.47	0.66	0.72	0.75	0.77	0.78	0.79	0.79	0.79	0.80
ADT.sim	0.25	1.15	227	0.50	0.69	0.75	0.78	0.79	0.79	0.80	0.80	0.81	0.81
ADU.sim	0.24	1.14	227	0.47	0.68	0.75	0.78	0.80	0.81	0.81	0.82	0.83	0.84
ADV.sim	0.22	1.13	227	0.43	0.69	0.76	0.79	0.81	0.82	0.83	0.84	0.84	0.85

The performance metric can also be used to assess how well the predicted time to exit the jumpform matches the experimental data for the jumpform. Using the predicted jumpform exiting data associated with the simulation that produced the smallest overall ERD, the metric values for the jumpform are presented in Table 40. In determining the SC value an appropriate value for the ratio *s/n* must be selected. This represents an appropriate value by which noise is filtered out of the experimental data. From the experimental curve presented in Figure 137a, bumps in the curve can involve two workers. To remove the influence of these bumps, an *s/n* value of 0.05 would be appropriate. Thus, an *s/n* of 0.05 represents 5% of the data-set and implies *s* = 2 for this data-set. As a result, for the 37-point data-set, the gradients used in the evaluation of Equation 13 are spread over two data points. Based on this approach, the values for the performance metric applied to the jumpform exiting data for the buildingEXODUS simulation producing the smallest ERD are:

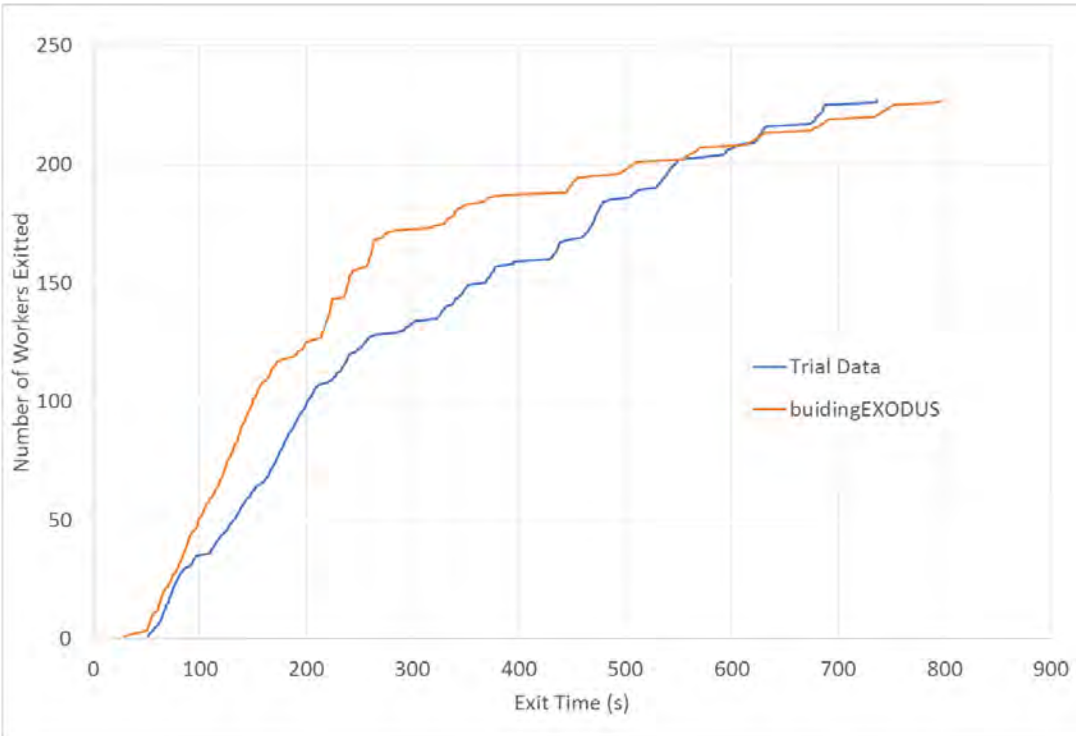
(i) ERD = 0.11
(ii) EPC = 1.02
(iii) SC = 0.80 with s/n = 0.05
(iv) Predicted total evacuation time for the jumpform (164 s) is under-predicted by 13%.

Table 40. Performance metric values for the jumpform exit curve derived from simulation producing the smallest overall ERD.

	ERD	EPC	n	s/n									
				0.01	**0.02**	**0.03**	**0.04**	**0.05**	**0.06**	**0.07**	**0.08**	**0.09**	**0.1**
ADT.sim	0.11	1.02	37	-	0.76	0.76	0.76	0.80	0.80	0.85	0.85	0.85	0.86



(a) The curve for the jumpform with minimum overall ERD.



(b) The exit curve for the entire building with minimum overall ERD.

Figure 137. The buildingEXODUS predicted exit curves with minimum overall ERD along with the experimental curve.

The performance metric values for the predicted jumpform exiting data suggest that the model prediction does a reasonable job in predicting the exiting time for the jumpform. As can be seen from Figure 137a, in many places the predicted exiting times are almost identical to the measured values (hence the relatively small value of ERD (0.11)) and the general shape of the predicted exit curve is a reasonable approximation to the experimental curve (hence the value of SC (0.80) being reasonably close to 1.0), and in general, the overall difference cannot be minimised by simply increasing or decreasing all the exit times as there are almost equal proportions of over-prediction and under-prediction (hence the EPC value being almost 1.0 (1.02)).

As stated previously, given the uncertainties in the experimental data (uncertain starting location for some workers, a lack of representation of clutter on the floors and an incomplete representation of the response time distribution), the level of agreement between the predicted and measured values is considered acceptable.

Thus, if other software tools produce a similar level of agreement using the generalised validation data-set, then the software would be considered to be as good as buildingEXODUS in reproducing the outcome of this trial. Furthermore, this performance can be used to define the minimum acceptability standard for this validation benchmark which is:

For the overall predicted exit curve:

(i) ERD ≤ 0.22
(ii) 0.87 ≤ EPC ≤ 1.13
(iii) SC ≥ 0.82 with s/n = 0.07
(iv) Difference between the predicted total evacuation time for the entire building and the measured value to be within 8%.

While for the predicted jumpform exit curve:

(i) ERD ≤ 0.11
(ii) 0.98 ≤ EPC ≤ 1.02
(iii) SC ≥ 0.80 with s/n = 0.05
(iv) Difference between the predicted total exiting time for the jumpform and the measured value to be within 13%.

This compares favourably to the previous standard used in the evaluation of the maritime validation data-set, which also had a number of uncertainties associated with the experimental data-set (see Section 5.2).

Key Finding 9.3: Objective performance of buildingEXODUS in validation scenario – Given the level of uncertainty in the validation data-set, an objective measure of acceptable agreement between model prediction and experimental data has been specified using the performance metric defined using the ERD, EPC and SC. The level of acceptability is based on the performance of the buildingEXODUS software, which was subjectively defined as being acceptable. Other software tools used to predict the outcome of the validation scenario producing a similar performance as measured using the metric would be considered to be as good as buildingEXODUS in reproducing the outcome of this trial. The performance measures are:

For the overall predicted exit curve:

(i) ERD ≤ 0.22
(ii) 0.87 ≤ EPC ≤ 1.13
(iii) SC ≥ 0.82 with s/n = 0.07
(iv) Difference between the predicted total evacuation time for the entire building and the measured value to be within 8%.

While for the predicted jumpform exit curve:

(i) ERD ≤ 0.11

(ii) ***0.98 ≤ EPC ≤ 1.02***

(iii) ***SC ≥ 0.80 with s/n = 0.05***

(iv) ***Difference between the predicted total exiting time for the jumpform and the measured value to be within 13%.***

5.5 Suggested validation framework

All members of the evacuation modelling communities are invited to make use of the construction site validation data-set to evaluate how a particular building evacuation modelling tool performs in simulating evacuation from construction sites.

The validation data-set is defined in this document (see Section 5.1) and is also available on the FSEG website at:
https://fseg.gre.ac.uk/validation/building_evacuation

The website describes the validation data-set and the process of carrying out a validation assessment using the data-set. The website provides all the required information to set-up and run the validation scenario within the users' evacuation software. In particular, the website describes the layout of the construction site (providing CAD DXF files), the initial population distribution, the end points for evaluation purposes, the population response time distribution and the arrival times for each worker at each end point. Other parameters to be used in the simulations, such as population gender, age distribution and travel speeds, are also described. All the information is also contained in this report.

The material described on the website is divided into ten sections, each dealing with a specific aspect of the validation data or validation procedures. These sections are:

- geometry: describes the layout of the construction site and provides information concerning the AutoCAD DXF files required to construct the geometry
- population: describes the distribution of the population, in particularly the start location of each agent in the model
- specific evacuation procedures: describes ad hoc evacuation procedures employed to regulate the flow of workers from the formworks
- response time distribution: describes the response time distribution which should be applied to the population
- exit curves: provides the exit curves for the jumpform and the building
- the validation metric: provides the measures to assess how closely the simulation results agree with the validation data-set
- procedures for running the validation scenario: describes the process of setting up and running the validation scenario. It also explains the process of selecting the appropriate simulation to be used in the validation analysis
- acceptance criteria: provides a set of suggested performance standards that the simulation results should meet in order to be deemed acceptable or as good as buildingEXODUS in performing the simulation
- regulatory documentation: provides a set of suggested documentation that should be provided to regulatory bodies to demonstrate that their software has met the standard
- additional information: provides a summary of all the files required to run and analyse the validation case.

Key Finding 9.4: Validation framework for assessing evacuation software suitability for construction site applications – A validation framework has been defined to carry out independent validation assessments using the validation data-set presented in this report. All the required information to set up and run the validation scenario within the users' evacuation software has been defined, including the layout of the construction site, the initial population distribution, the end points for evaluation purposes, the population response time distribution and the arrival times for each worker at each end point. Other parameters to be used in the simulations, such as population gender, age distribution and travel speeds, are also described. A means of objectively assessing the performance of the software in reproducing the validation scenario has also been defined along with levels of acceptable performance based on the relative performance of the software with that of the buildingEXODUS software.

5.6 Summary of the main results

In this section a validation data-set for evacuation models attempting to simulate evacuation from high-rise construction sites has been defined. A performance metric has been defined to objectively describe the goodness of fit between model predictions and experimental data. Furthermore, given the level of uncertainty in the validation data-set, an objective measure of acceptable agreement between the model prediction and the experimental data has been specified for the performance metric. The level of acceptability is based on the performance of the buildingEXODUS software which was objectively defined as producing an acceptable level of agreement with the experimental data. Using this approach, a validation framework has been defined to allow independent assessments of other software tools used to predict the outcome of the validation scenario.

The conclusion of this section describes the successful completion of project Task 4 addressing the requirements of project Objective 4.

6 Using the validated evacuation model to explore improvements to construction site evacuation

To demonstrate the potential use of the validated evacuation simulation software and data-sets to high-rise construction site applications, several modifications to evacuation procedures on high-rise construction sites are systematically examined and potential improvements in evacuation performance quantified. The modifications investigated are:

- improving the response time of workers
- replacing ladders with temporary stairs in the formwork
- use of hoists for evacuation.

This section describes the work undertaken as part of project Task 5 to address project Objective 5.

6.1 The benchmark cases

When assessing the impact of the proposed modifications, it is necessary to have a base case or benchmark for comparison purposes. Ideally, several benchmark cases would be defined in order to assess the robustness of the potential improvements to a range of scenarios. However, we define two benchmark cases in this task and leave further test of the robustness for further work.

6.1.1 Benchmark scenarios

Two benchmark cases are considered, both of which are based on the 100 BG configuration from Trial 1. In the first benchmark scenario (BMS1), the geometry closely resembles 100 BG and consists of 22 levels. The second benchmark scenario (BMS2) is similar to BMS1 but consists of 42 levels. An additional 20 levels are added to the structure; however, the first 20 levels are considered completed.

6.1.2 BMS1 geometry

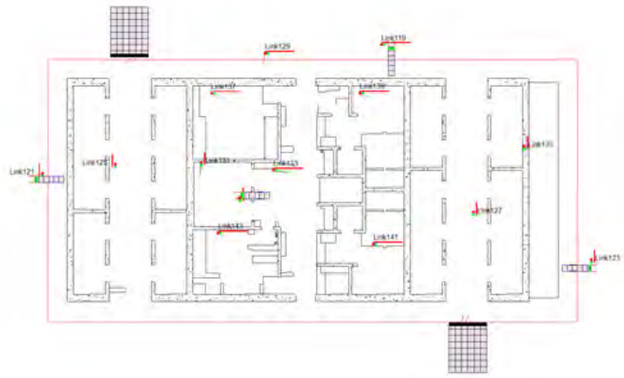
The geometry used in BMS1 consists of a building layout approximating that of the 100 BG configuration from Trial 1. The configuration consists of 22 levels, from ground (Level 0) to the top deck of the slipform at Level 21:

- from ground (Level 0) to Level 11 (consisting of 12 levels) are either floors that have been recently completed or in the process of completion
- from Level 12 to Level 19 (consisting of eight levels) are core-only levels
- Level 20 is the base of the slipform with the top deck at Level 21 (22 levels).

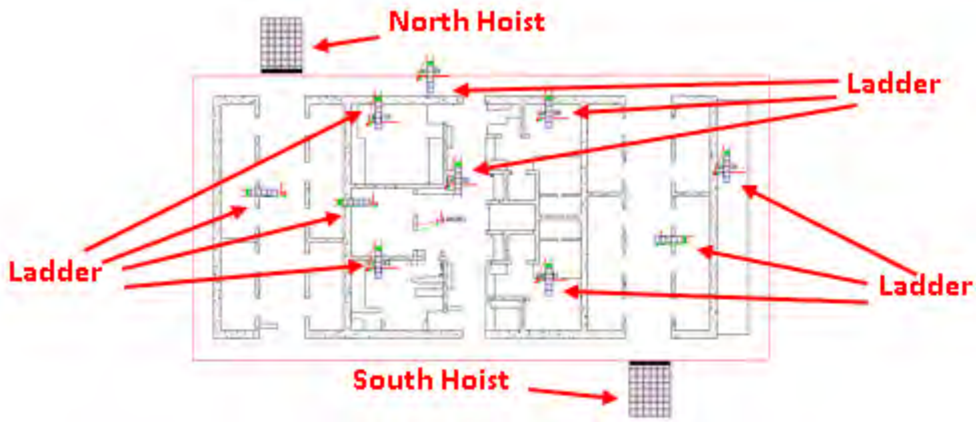
Note the 22 levels in BMS1 are counted from the ground level (Level 0) to the top deck of the slipform located at Level 21.

The layout of the entire building is presented in Figure 138. Each depicted layout is repeated for each level in the identified section. For example, the layout in Figure 138e is repeated for each level from Level 1 to Level 13. It is noted that there is no clutter on any of the floors and all floor surfaces are concrete. The exit from the building and the end point for the simulation is a 2 m wide exit on the ground floor (see Figure 138f).

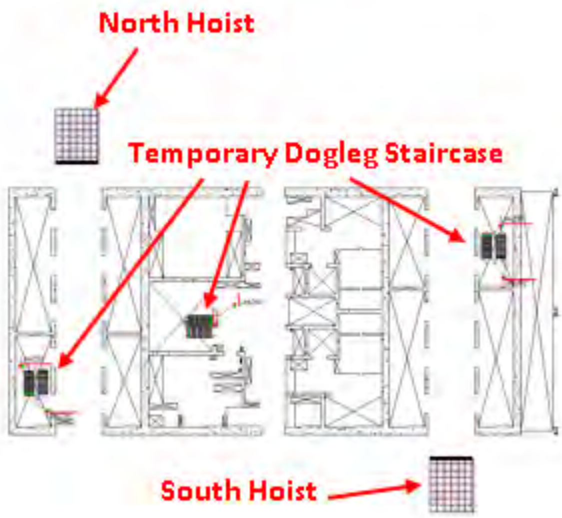
(a) Layout of Level 21 (top deck of slipform).



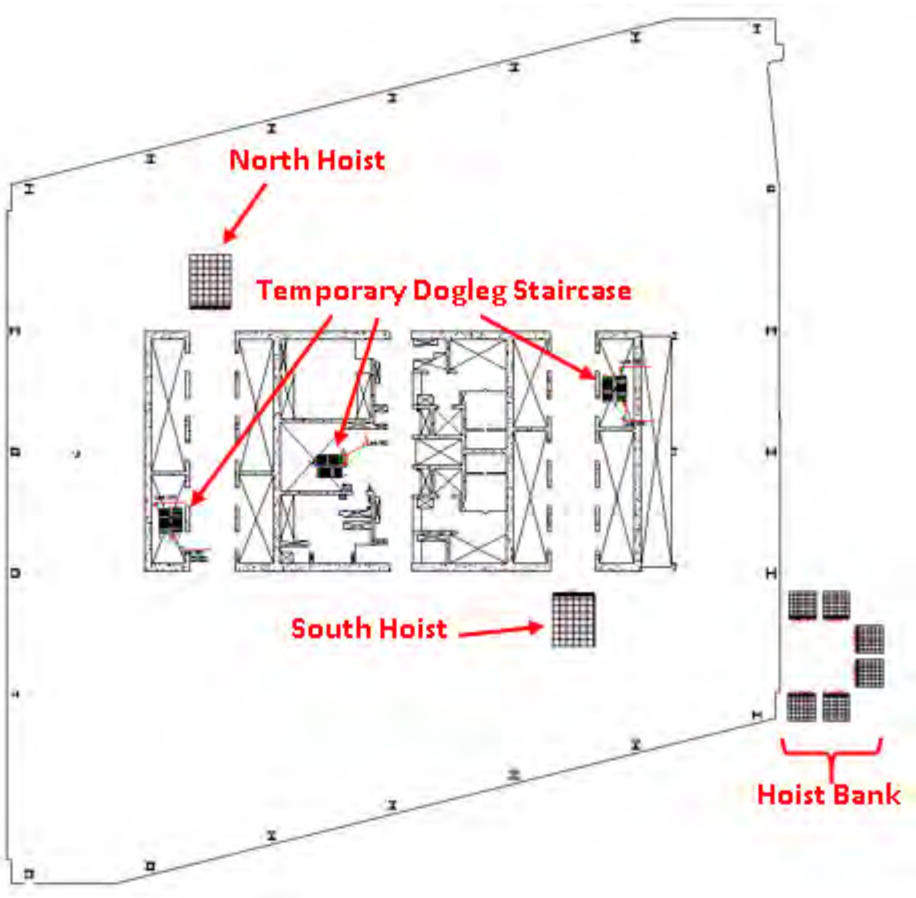
(b) Layout of mid deck of slipform.



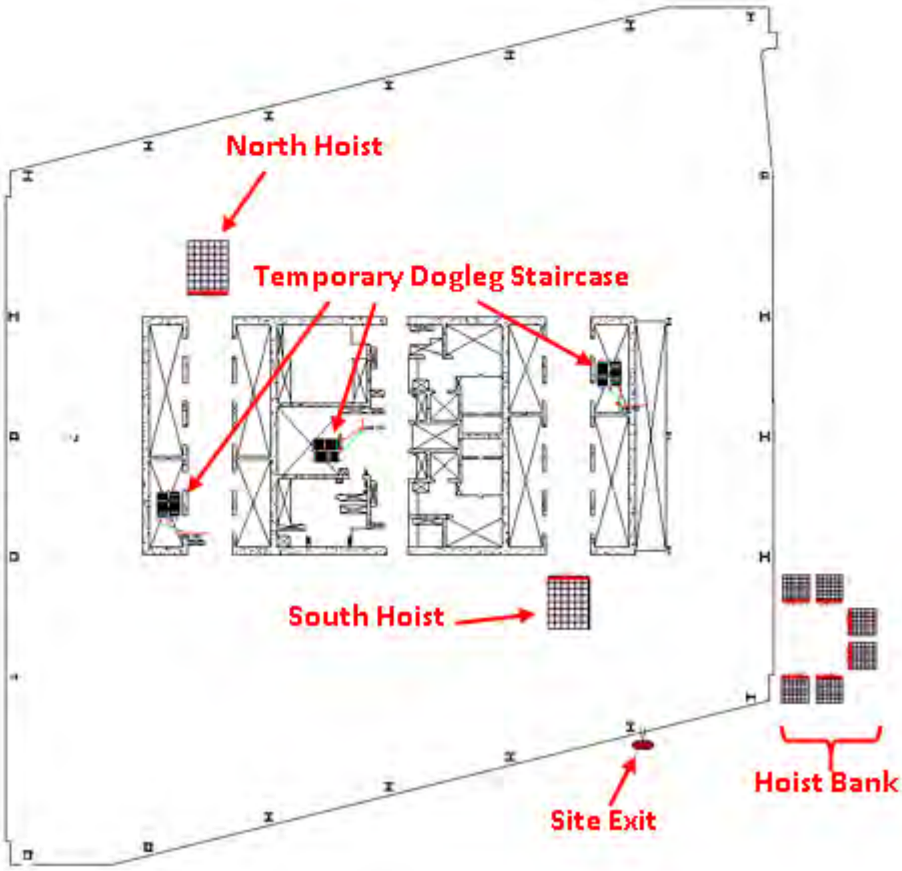
(c) Layout of Level 20 (bottom deck of slipform).



(d) Layout of Level 12 to Level 19.



(e) Layout of Level 1 to Level 11.



(f) Layout of ground floor (Level 0).

Figure 138. Layout of building used in BMS1 scenarios.

The geometry has three temporary scaffold dogleg staircases which extend from the ground level (see Figure 138f) up through the core to the level below the slipform (see Figure 138d). The middle of the three staircases extends to the base of the slipform and acts as the only egress route from the slipform. At the base of the three temporary staircases are the three exits from the building. The slipform has 10 ladders on the lower deck that extend up to the middle deck. There are four ladders on the middle deck which connect to the top deck of the slipform. The only exit route from the slipform is via a discontinuous ladder which links the top deck to the lower deck. This ladder can only be accessed from the top deck (see Figure 21).

The building has eight hoists. Two hoists, labelled North Lift Shaft and South Lift Shaft, service the slipform. The other six hoists, labelled Hoist Bank 1 to Hoist Bank 6, are located in the south-east corner of the construction site (see Figure 138f). These hoists can service every completed floor. There are two types of hoist in the building: the Raxtar RX3245SF and the Alimac Scando 650FC. The approximated performance of each of these hoists (as implemented within the buildingEXODUS software) is summarised in Table 41.

Table 41. Approximated hoist performance capabilites as implemented within the model.

	Raxtar RX3245SF	Alimac Scando 650FC
Passenger capacity	40	30
Max speed (m/s)	1.53	0.7
Acceleration (m/s^2)	0.3	0.35
Deceleration (m/s^2)	0.8	0.35
Opening time (s)	5	4
Closing time (s)	1	2
Dwell time (s)	3	3
Motor delay (s)	4	0.5

6.1.3 BMS2 geometry

The geometry used in BMS2 consists of a building layout similar to that of BMS1 but raised by 20 levels, making the building 42 levels in total. From ground level (Level 0) to Level 19 (20 levels) are completed levels, from Level 20 to Level 31 (12 levels) are either floors that have been recently completed or in the process of completion, from Level 32 to Level 39 (eight levels) are core-only levels, with the slipform at Level 40 (the top deck of the slipform at Level 41). The interior layout is identical to that of BMS1.

6.1.4 Benchmark population

As part of the benchmark case, the building has a population of 525 agents: 125 in the slipform and 400 distributed randomly throughout the rest of the building. Two response time distributions were used:

- for the slipform the HPFW response time distribution specified in Equation 5 (see Section 4.6.1.4) was used
- for the main building the MB response time distribution specified in Equation 10 (see Section 4.6.2.3) was used.

In BMS1, the main building population is distributed between Level 0 and Level 19 (20 levels) while in BMS2, the main building population is distributed between Level 20 and Level 39 (20 levels). The building population is summarised in Table 42. The population distribution represents the average, maximum and minimum derived from each scenario for the 100 repeat simulations. As the presented numbers represent averages over each scenario and each 100 repeat simulations per scenario, the totals will not add up to 400 agents in the main building and 125 agents in the formworks. However, in each simulation the correct number of agents were located within the building.

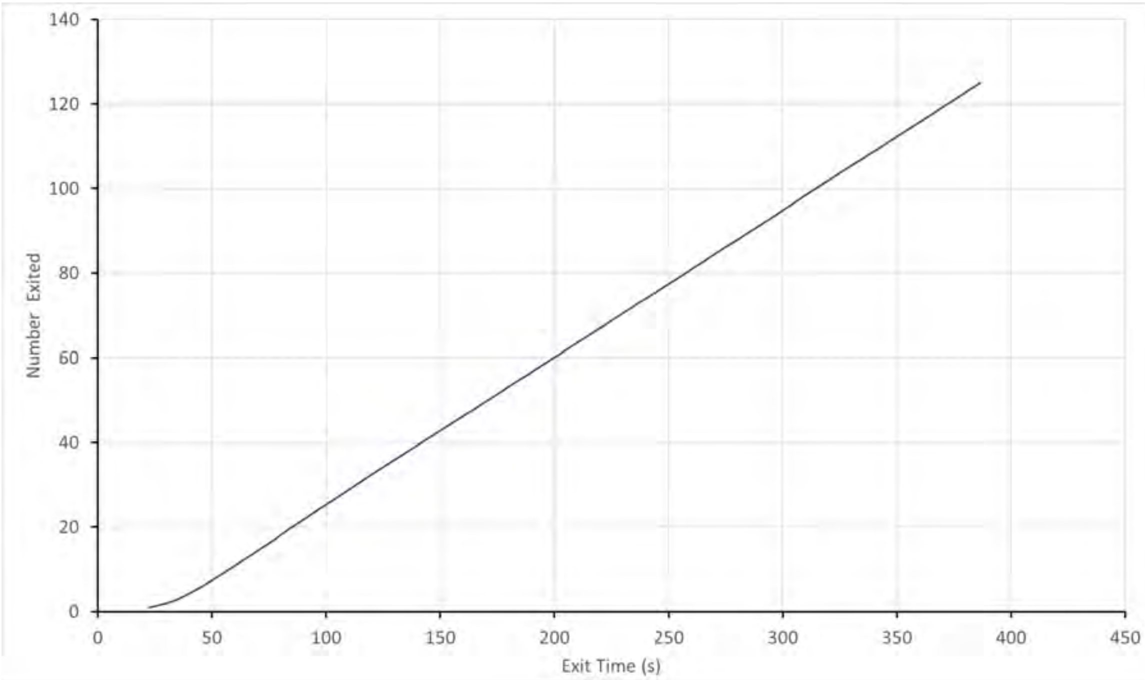
Table 42. Population distribution used in BMS1 and BMS2.

Level BMS1/BMS2	Overall (BMS1 and BMS2)			BMS1			BMS2		
	Min	Average	Max	Min	Average	Max	Min	Average	Max
0/20	19	32	45	19	31	44	19	32	47
1/21	18	32	46	18	32	46	19	31	46
2/22	19	32	46	19	32	46	19	32	45
3/23	19	31	46	19	32	47	19	31	46
4/24	19	32	46	19	32	47	20	32	45
5/25	19	31	46	18	31	46	19	31	46
6/26	19	32	46	18	31	46	19	32	46
7/27	19	31	45	19	32	45	20	31	45
8/28	19	32	46	19	31	46	19	32	46
9/29	18	32	45	19	32	45	18	32	45
10/30	19	32	46	20	32	47	19	31	45
11/31	19	32	45	19	32	46	20	32	45
12/32	0	3	8	0	3	8	0	3	7
13/33	0	3	7	0	3	7	0	3	8
14/34	0	3	8	0	3	8	0	3	8
15/35	0	3	7	0	3	7	0	3	7
16/36	0	3	8	0	3	8	0	3	7
17/37	0	3	8	0	2	7	0	3	8
18/38	0	3	8	0	3	7	0	3	8
19/39	0	3	8	0	3	8	0	3	8
20/40 Slipform Lower deck	31	43	56	32	43	56	31	43	56
Slipform Mid deck	32	45	58	32	45	57	33	45	60
21/41 Slipform Upper deck	25	37	50	24	37	51	25	37	49

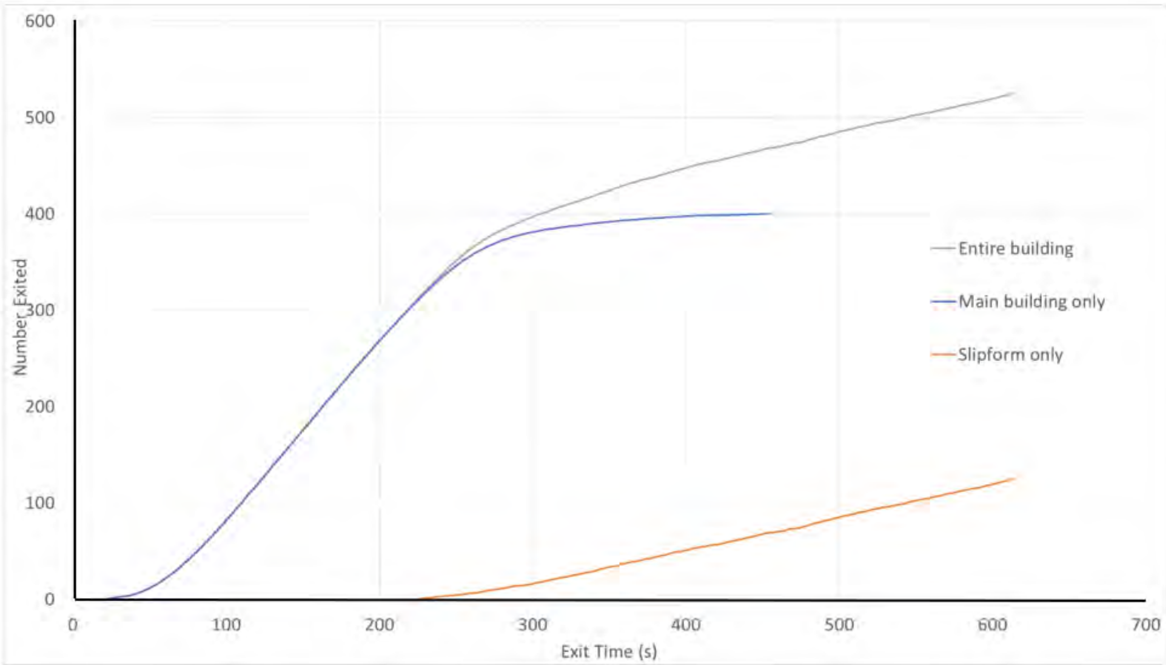
6.1.5 BMS1 results

The benchmark scenario was repeated 100 times. Within each simulation the starting location of the population within both the slipform and the main building was randomly allocated and the response times were randomly allocated from the appropriate distribution. As a basis of comparison with the modified cases, we take the average exit curve as a representative model prediction for the benchmark scenario. This is determined by taking the average time for each agent to exit from the 100 repeat simulations. Presented in Figure 139 are the average predicted exit curves for the slipform (Figure 139a) and the entire building (Figure 139b). The exit time from the slipform is determined as the time at which each agent exits the ladder from the slipform and sets foot on Level 19.

Presented in Table 43 are the times for various percentiles to exit the building for the entire population, the main building population and the slipform population. We note that the average predicted time to empty the building is 613 s, with the last person from the main building exiting at 459 s – the last person to exit the building is from the slipform. Indeed, when the first person from the slipform exits the building at 227 s, 314 (79%) workers from the main building population have exited. On average, 86 main building workers interact with the slipform workers during the evacuation. When the last main building worker has exited (459 s), 69 (55%) of the slipform workers have exited, leaving 56 yet to exit. Thus, the tail of the exit curve, representing 11% (56) of the entire population is made up of slipform workers.



(a) The exit curve from the slipform.



(b) The exit curves for the entire building.

Figure 139. The average buildingEXODUS predicted exit curves for BMS1.

Presented in Table 44 are the times for various percentiles to exit the slipform (arrive on Level 19). We note that the average predicted time for all the workers to exit the slipform is 387 s, with 50% (63) of the slipform population exiting by 208 s.

Table 43. Predicted (average values) building exit times for BMS1.

Benchmark	1st	50%	75%	90%	98%	100%	Mean
Entire building (s)	22.5 (1)*	198 (263)	297 (394)	475 (472)	591 (514)	613 (525)	232
Main building (s)	22.5 (1)	164 (200)	219 (300)	264 (360)	359 (392)	459 (400)	169
Slipform (s)	227 (1)	441 (63)	527 (94)	584 (113)	612 (123)	613 (125)	435

* Figures in brackets represent number of agents exited.

Table 44. Predicted (average values) times to exit the slipform for BMS1.

Benchmark	1st	50%	75%	90%	98%	100%	Mean
Slipform (s)	22.5 (1)*	208 (63)	298 (94)	352 (113)	381 (123)	387 (125)	208

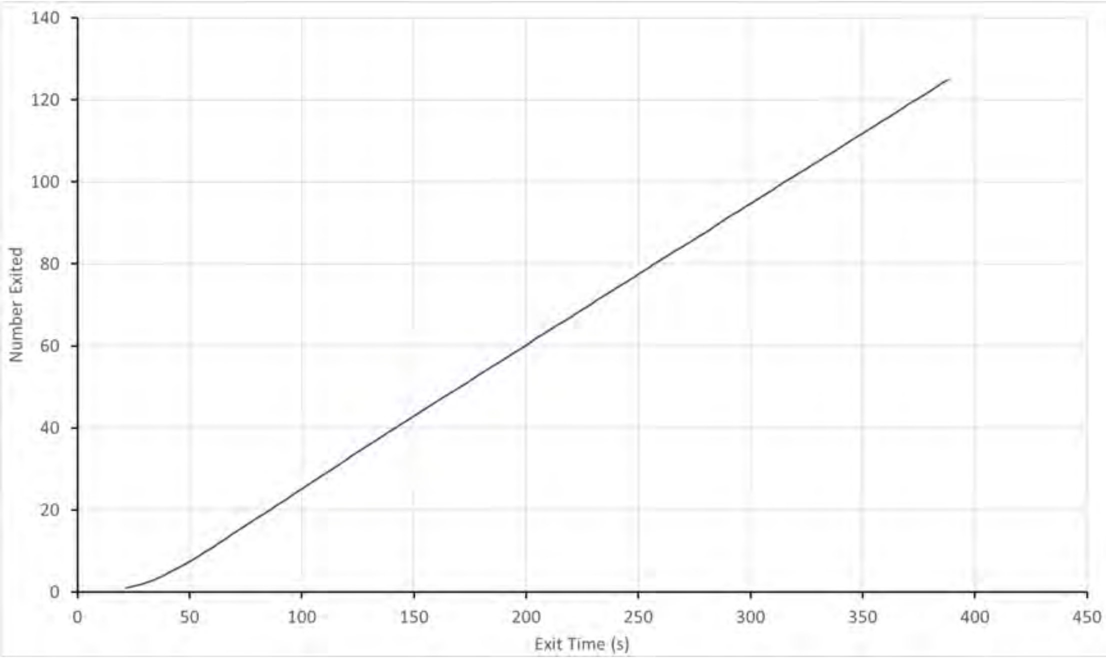
* Figures in brackets represent number of agents exited.

6.1.6 BMS2 results

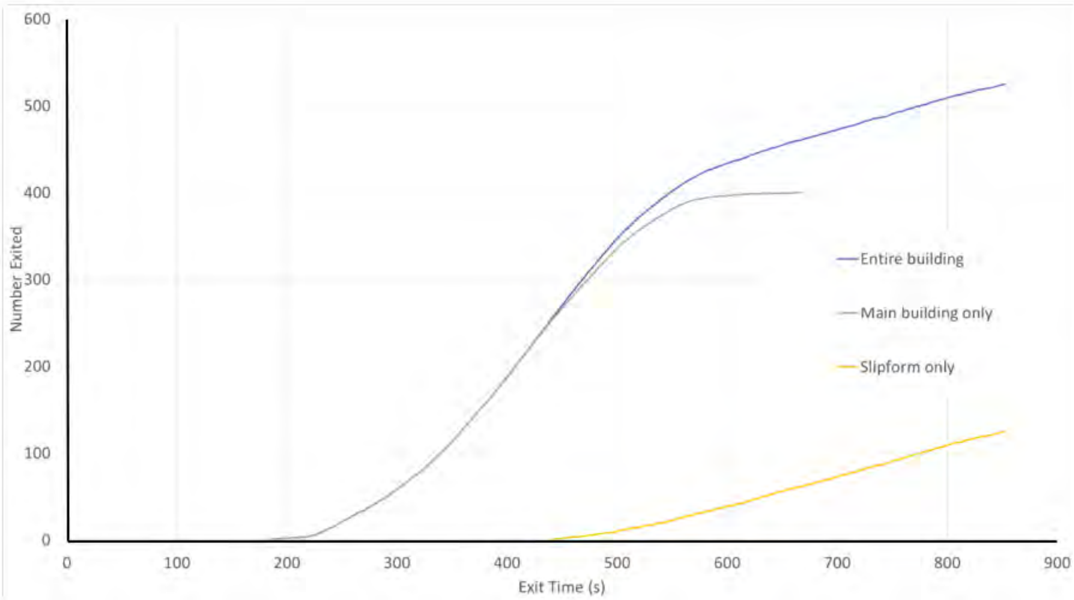
The benchmark scenario was repeated 100 times. Within each simulation the starting location of the population within both the slipform and the main building was randomly allocated, and the response times were randomly allocated from the appropriate distribution. As a basis of comparison with the modified cases, we take the average exit curve as a representative model prediction for the benchmark scenario. This is determined by taking the average time for each person to exit from the 100 repeat simulations. Presented in Figure 140 are the average predicted exit curves for the slipform (Figure 140a) and the entire building (Figure 140b). The exit time from the slipform is determined as the time at which each agent exits the ladder from the slipform and sets foot on Level 39.

Presented in Table 45 are the times for various percentiles to exit the building for the entire population, the main building population and the slipform population. We note that the average predicted time to empty the building is 852 s, with the last person from the main building exiting at 668 s – the last person to exit the building is from the slipform. Indeed, when the first person from the slipform exits the building at 440 s, 252 (63%) workers from the main building population have exited. On average, 148 main building workers interact with the slipform workers during the evacuation. When the last main building worker has exited (668 s), 62 (50%) of the slipform workers have exited, leaving 63 yet to exit. Thus, the tail of the exit curve, representing 12% (63) of the entire population is made up of slipform workers.

Presented in Table 46 are the times for various percentiles to exit the slipform (arrive on Level 39). We note that the average predicted time for all the workers to exit the slipform is 388 s, with 50% (63) of the slipform population exiting by 208 s.



(a) The exit curve from the slipform.



(b) The exit curves for the entire building.

Figure 140. The average buildingEXODUS predicted exit curves for BMS2.

Table 45. Predicted (average values) building exit times for BMS2.

Benchmark	1st	50%	75%	90%	98%	100%	Mean
Entire building (s)	183 (1)*	446 (263)	543 (394)	703 (472)	821 (514)	852 (525)	468
Main building (s)	183 (1)	408 (200)	474 (300)	525 (360)	575 (392)	668 (400)	405
Slipform (s)	440 (1)	674 (63)	762 (94)	815 (113)	850 (123)	852 (125)	666

* Figures in brackets represent number of agents exited.

Table 46. Predicted (average values) times to exit the slipform for BMS2.

Benchmark	1st	50%	75%	90%	98%	100%	Mean
Slipform (s)	21.6 (1)*	208 (63)	298 (94)	353 (113)	382 (123)	388 (125)	209

* Figures in brackets represent number of agents exited.

6.1.7 Comparing BMS1 and BMS2

Presented in Table 47 are key building exiting times for the entire population, the main building population and the slipform population in BMS1 and BMS2. We note, as expected, that the exiting times for the higher building are all longer than those for the shorter building and from Figure 141 we note that the exiting curve for the higher building appears to be shifted towards the longer exiting times by approximately 240 s. Thus, adding an additional 20 levels to the building has simply extended all workers' travel distance and hence exit times. It is also noted that the time required to empty the slipform is identical in both cases (see Table 44 and Table 46 for BMS1 and BMS2 respectively).

Table 47. Predicted (average values) building exit times for BMS1 and BMS2.

Benchmark	1st		50%		75%		100%	
	BMS1	BMS2	BMS1	BMS2	BMS1	BMS2	BMS1	BMS2
Entire building (s)	22.5 (1)*	183 (1)	198 (263)	446 (263)	297 (394)	543 (394)	613 (525)	852 (525)
Main building (s)	22.5 (1)	183 (1)	164 (200)	408 (200)	219 (300)	474 (300)	459 (400)	668 (400)
Slipform (s)	227 (1)	440 (1)	441 (63)	674 (63)	527 (94)	762 (94)	613 (125)	852 (125)

* Figures in brackets represent number of agents exited.

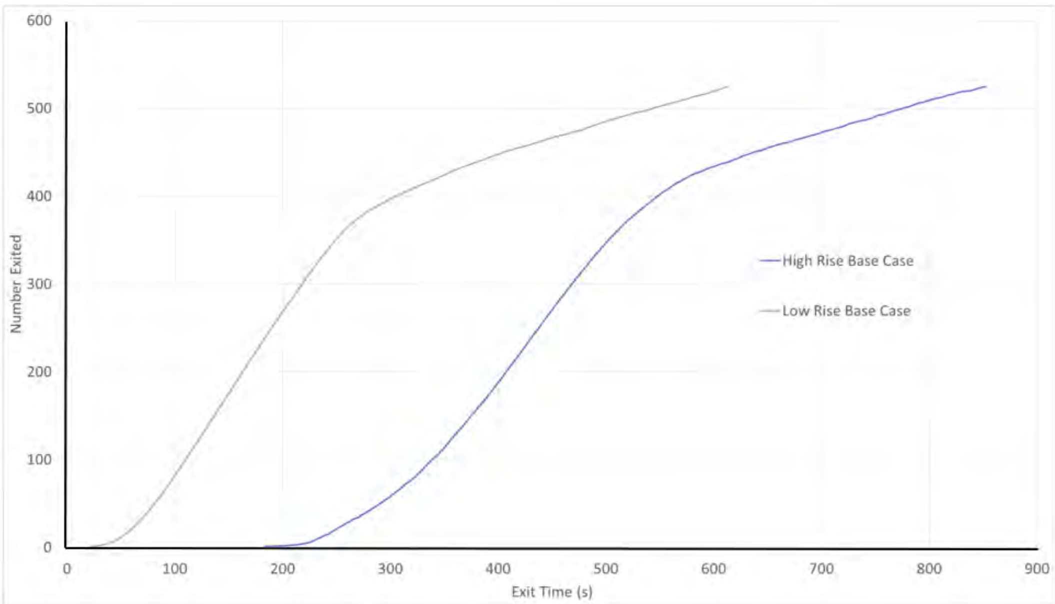


Figure 141. The average buildingEXODUS predicted exit curves for BMS1 and BMS2.

6.2 Impact of improved response time on evacuation performance

The first concept to be explored to improve overall evacuation performance involves reducing occupant response times. One approach to reducing overall response times is through enhanced training where the importance of responding quickly is emphasised. If enhanced training were used as a means to reduce the response times, and if it were successful, it could be assumed that the response times for all workers would be reduced by some factor. However, if this approach were successful, it would take some time to implement as all the workers would need to undergo the required training and it would not assist in situations where the worker cannot hear the alarm.

Another way of improving response times is through supervisor intervention. In Section 4.3.1 it was noted that when supervisors intervened with workers this encouraged the workers to more rapidly disengage from their pre-alarm activities and engage in evacuation activities. In some cases, supervisors were very effective in forcing workers to start the evacuation process. If the use of additional supervisors is used as a means to reduce response times, then only a selection of workers would have their response times reduced, i.e. those that came into contact with the supervisors.

A third way of potentially reducing response times is through the introduction of technology. It was noted in Section 4.1.1 and Section 4.4.1 that some workers failed to hear the fire alarm, in particular isolated workers wearing ear protectors. One possible approach to address this is to issue each worker with a pocket pager that vibrates on alarm. The workers could be issued with the pager each day as they check in to the construction site. Alternatively, each worker's mobile phone could be registered and a vibrate alert automatically sent to their phone during an emergency. Another possibility is to have a vibrator built into the head protection worn by workers which would again vibrate during an emergency. Using such technology would automatically alert all workers on the site and so is likely to impact the response times of all workers. A disadvantage is the need to introduce new technology in the form of devices or software apps and the need to keep physical devices charged.

In this analysis we assume that additional supervisors are engaged on the construction site and these staff are effective in reducing the response times of workers, but only a proportion of the workers present, i.e. those whom the supervisors may come into contact with.

Finding 10.1: Reducing response times of construction site workers 1 – Several approaches are suggested to reduce the response times of workers on high-rise construction sites. These could involve:

- ***specific training highlighting the importance of a rapid response to the alarm and what rapid response means. This action is likely to result in a reduction of the response times of all workers but does not assist in situations with isolated workers who cannot hear the alarm***
- ***increasing the number of supervisors on site who are able to assertively intervene with workers during an emergency situation. This action is likely to result in a reduction in response times for only a few workers whom the supervisors come into contact with***
- ***introducing technology such as pagers, use of mobile phones or novel new devices such as vibrating head protection. This action is likely to result in the reduction of response times for all workers but has the disadvantage of requiring the introduction of new technology and the need to keep devices charged.***

6.2.1 The adjusted response time distribution

It is difficult to assess how effective a single supervisor will be in reducing worker response times and the number of workers a single supervisor could influence. Thus, the proposed change in response time distribution is intended to be for demonstration purposes. Only the main building response times are modified (i.e. Equation 10 in Section 4.6.2.3). In total, the generalised response time distribution for the main building was based on the measured response times of 182 workers. Here we assume that through the introduction of several additional supervisors, six workers with the longest response times have their response times halved due to the intervention of the additional supervisors. In addition, another 30 workers selected at random with relatively long response times, in the range of

100 s to 200 s, are targeted by the additional supervisors and also have their response times halved. Thus, in total 36 workers, representing 20% of the original sample, have their response times effectively halved through the intervention of supervisors. This results in the modified response time distribution presented in Figure 142. The difference in the response time distributions is summarised in Table 48. As can be seen, the changes to the response time distribution are modest, the main difference being the reduction in the maximum response times that are allocated to the population.

Finding 10.2: Reducing response times of construction site workers 2 – It is argued that introducing additional supervisors into the main building could result in a reduction in response time for the workers resulting from enhanced supervisor intervention during an emergency. In the case proposed, the average response time of the workers was reduced from 71 s to 52 s, a reduction of 27%. This was primarily achieved by halving the response times of workers with high response times, which resulted in the maximum response time being reduced from 340 s to 198 s, a reduction of 142 s or 42%.

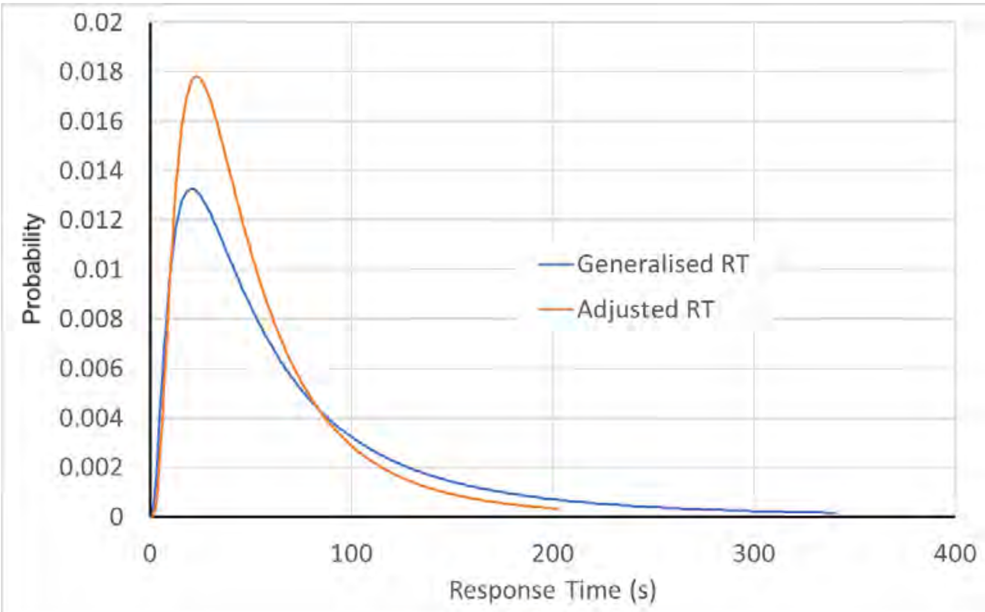


Figure 142. The generalised and modified response time distribution for the main building.

Table 48. The generalised and modified response time distribution.

	Min RT (s)	Max RT (s)	Mean RT (s)	Standard Deviation
Original RT Distribution	0	340	71.5	58.1
Modified RT Distribution	0	198	52.1	29.9

6.2.2 Impact of reduced response time in high-rise construction up to 22 levels

The model was run again using the adjusted response time distribution (see Figure 142) for 100 simulations. When analysing these results, it must be recalled that the reduction in response times only applies to the agents in the main building. As the overall time required to evacuate the building is driven by the time required by the slipform workers to exit, this will not be affected by the reduction in response times in this case.

Presented in Figure 143 are the exit curves for BMS1 and the corresponding case with the reduced response times, while in Table 49 several exit times for key percentiles of various populations are presented. As can be seen, the time for the slipform workers to exit the building is identical in the two cases, and as a result, the overall evacuation time for the building has not changed and the time for the final 14% (74) of the building population (made up entirely of slipform workers) to exit is identical in both cases.

Nevertheless, there is a marked decrease in the time for the main building population to evacuate. By the time 50% (263) of the building population has evacuated, the average evacuation time has decreased by 5% (10 s). By the time all the agents in the main building have evacuated (400), the evacuation time for the main building population has decreased from 459 s to 340 s (119 s or 26%).

Finding 10.3: Impact on evacuation times of achieving a reduction in worker response time for high-rise construction up to 22 levels – Applying the adjusted response time distribution for the main building, resulting in a 27% reduction of the average response time for workers in the main building and reducing the maximum response time by 42%, results in a 26% decrease in the average total evacuation time for the workers in the main building. However, the overall evacuation time for the building has not changed as the workers in the slipform, who are the last to evacuate, are not affected by the reduction in response times. The improvement in evacuation times for the main building applies to high-rise construction sites of up to 22 levels.

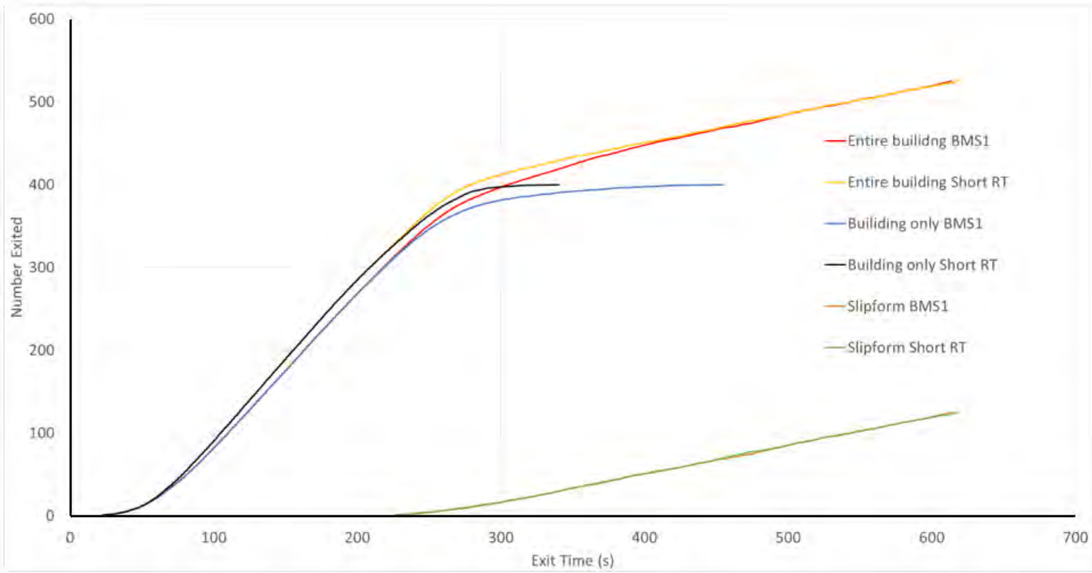


Figure 143. The average buildingEXODUS predicted exit curves for BMS1 and BMS1 with reduced RT.

Table 49. Predicted (average values) building exit times for BMS1 and reduced RT.

Benchmark	**1st**		**50%**		**75%**		**100%**	
	BMS1	Reduced RT	BMS1	Reduced RT	BMS1	Reduced RT	BMS1	Reduced RT
Entire building (s)	22.5 (1)*	23.6 (1)	198 (263)	188 (263)	297 (394)	272 (394)	613 (525)	619 (525)
Main building (s)	22.5	23.6	164	156	219	210	459	340

	(1)	(1)	(200)	(200)	(300)	(300)	(400)	(400)
Slipform (s)	227 (1)	226 (1)	441 (63)	439 (63)	527 (94)	524 (94)	613 (125)	619 (125)

* Figures in brackets represent number of agents exited.

6.2.3 Impact of reduced response time in high-rise construction up to 42 levels

As in the previous case (up to 22 levels), the overall time required to evacuate the building is driven by the time required by the slipform workers to exit; this time will not be impacted by the reduction in response times in this case.

Presented in Figure 144 are the exit curves for BMS2 (higher construction) and the corresponding case with the reduced response times, while in Table 50 several exit times for key percentiles of the various populations are presented. As can be seen, the time for the slipform workers to exit the building is practically identical in the two cases, and as a result, the overall evacuation time for the building has not changed and the time for the final 12% (63) of the building population (made up entirely of slipform workers) to exit is practically identical in both cases.

Nevertheless, there is a marked decrease in the time for the main building population to evacuate. By the time 50% (263) of the building population has evacuated, the average evacuation time has decreased by 2% (8 s). By the time all the agents in the main building have evacuated (400), the evacuation time for the main building population has decreased from 668 s to 586 s (82 s or 12%).

Finding 10.4: Impact on evacuation times of achieving a reduction in worker response time for high-rise construction up to 42 levels – Applying the adjusted response time distribution for the main building, resulting in a 27% reduction of the average response time for workers in the main building and reducing the maximum response time by 42%, results in a 12% decrease in the average total evacuation time for the workers in the main building. However, the overall evacuation time for the building has not changed as the workers in the slipform, who are the last to evacuate, are not affected by the reduction in response times. The improvement in evacuation times for the main building applies to high-rise construction sites of up to 42 levels.

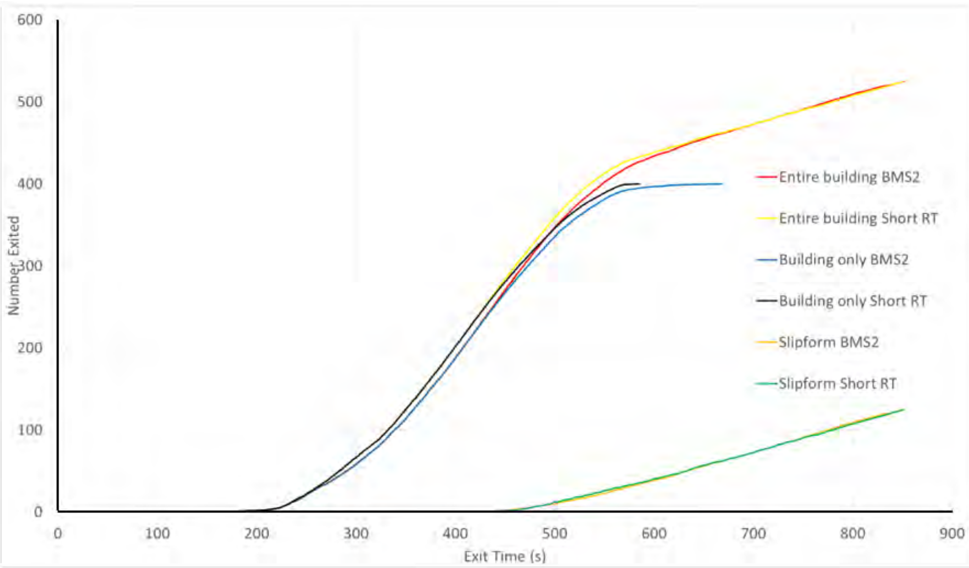


Figure 144. The average buildingEXODUS predicted exit curves for BMS2 and BMS2 with reduced RT.

Table 50. Predicted (average values) building exit times for BMS2 and reduced RT.

Benchmark	1st		50%		75%		100%	
	BMS2	Reduced RT	BMS2	Reduced RT	BMS2	Reduced RT	BMS2	Reduced RT
Entire building (s)	183 (1)*	189 (1)	446 (263)	438 (263)	543 (394)	531 (394)	852 (525)	850 (525)
Main building (s)	183 (1)	189 (1)	408 (200)	400 (200)	474 (300)	465 (300)	668 (400)	586 (400)
Slipform (s)	440 (1)	441 (1)	674 (63)	673 (63)	762 (94)	767 (94)	852 (125)	850 (125)

* Figures in brackets represent number of agents exited.

It is noted that increasing the height of the construction, and thereby placing the building population further from the exit point, tends to decrease the impact of reducing the worker response times. When the workers in the main building were positioned from Level 0 to Level 19, a 27% reduction in the average response time resulted in a 26% decrease in the evacuation time for the main building population (excluding those in the slipform). In contrast, when the workers are positioned from Level 20 to Level 39 (a 20-levels increase in height), the evacuation time for the main building population decreased by 12% for the same 27% decrease in their average response time. This is due to the greater time that the workers spend travelling down the stairs with the higher construction.

Key Finding 10.1: Impact on evacuation times of a targeted reduction in worker response times – In high-rise construction sites with a population of 525 occupants, decreasing the response time for workers in the main building, resulting in a 27% reduction of the average response time for workers in the main building and reducing the maximum response time by 42%, results in a 26% or 12% decrease in the average total evacuation time for the workers in the main building for construction sites of up to 22 levels and 42 levels respectively (including the formworks). These results suggest that substantial improvements in total evacuation time for the main building can be achieved by reducing the response times of some of the slowest responders. However, the improvement gains in total evacuation time achieved by reducing the average response time of the main building population diminish with increasing height of construction. It is also noted that the overall evacuation time for the building is not altered as the 125 workers located in the formworks, who are the last to evacuate, are not affected by the reduction in response times.

6.2.4 Impact of 50% reduction in response time in high-rise construction of up to 22 levels

In order to estimate the impact of a more significant reduction in response time on overall evacuation time, the response time of every worker, both in the main building and the slipform, was halved. This significant reduction in response time might be achieved by a combination of all the methods suggested in Section 6.2. This reduces the average response time for the main building population from 71.5 s to 34.8 s (51%) and the average response time of the slipform workers from 65.7 s to 32.8 s (50%). The reduced response time distributions are applied to workers in the BMS1 case (22 levels), resulting in the exit graph shown in Figure 145.

With this more significant reduction in response time, by the time 50% (263) of the building population has evacuated, the average evacuation time has decreased by 12% (24 s). Furthermore, by the time all the agents in the main building have evacuated (400), the evacuation time for the main building population has decreased by 33% (153 s). However, the overall evacuation time of the building has only improved by 1% (7 s) (see Table 51). While not explored in this analysis, it is expected that the reduction in total evacuation time for the main building will be less significant with increasing height of construction.

Table 51. Predicted (average values) building exit times for BMS1, BMS1 with reduced RT and BMS1 with halved RT.

	BMS1 (s)	BMS1 with reduced RT (s)*	BMS1 with halved RT (s)
50% of entire building pop (263)	198	188	174
100% of main building pop (400)	459	340	306
100% of entire building pop (525)	613	619	606

* Simulation results from Section 6.2.2.

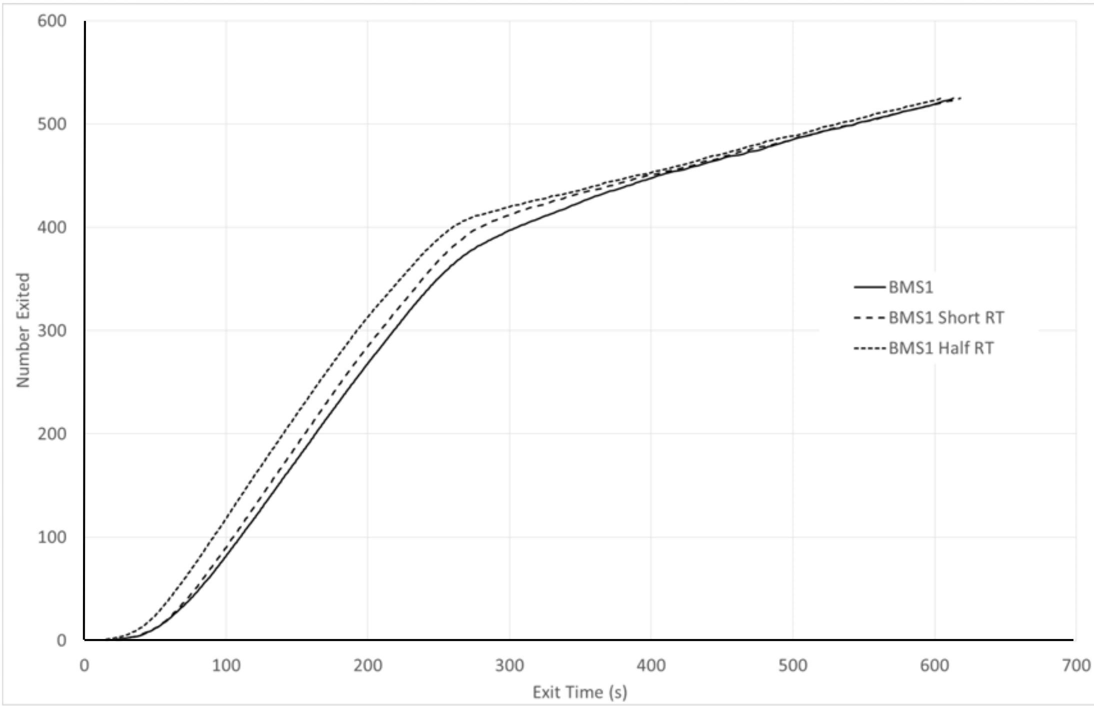


Figure 145. The average buildingEXODUS predicted exit curves for BMS1, BMS1 with reduced RT and BMS1 with 50% reduction in RT.

This modest improvement in the total evacuation can be explained by considering the exit times for the slipform. As can be seen in Figure 146, even with a reduction of 50% in the response times for the workers in the slipform, there is only a 3% reduction in the time to clear the slipform (388 s to 377 s).

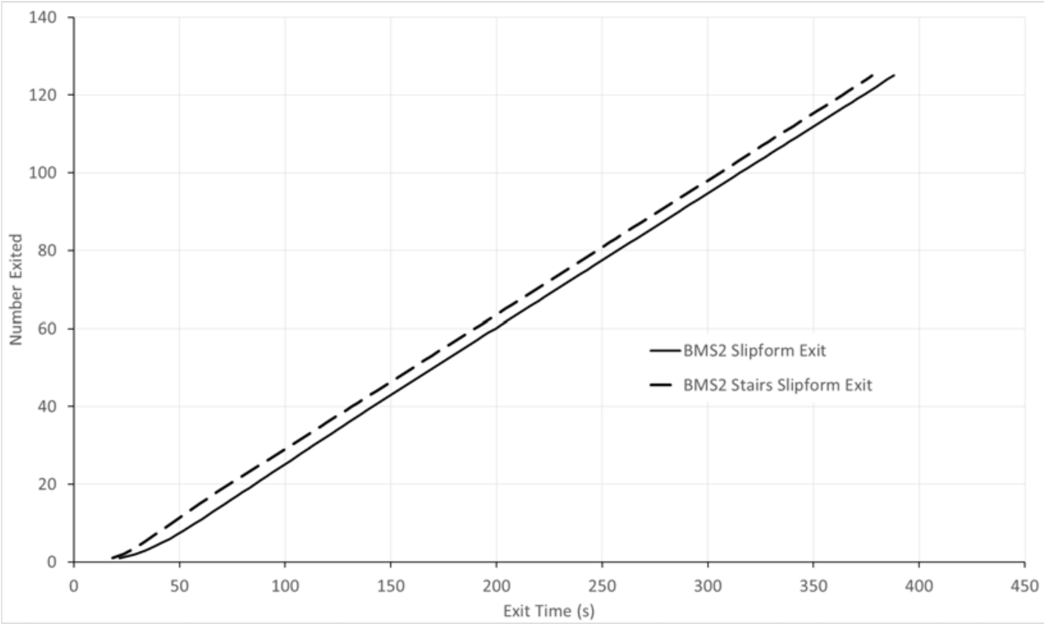


Figure 146. The average buildingEXODUS predicted slipform exit curves for BMS1 and BMS1 with 50% reduction in response times.

The reason for this limited improvement in the time to clear the slipform is the congestion in the slipform around the only means of egress: the single ladder. Within the simulation, congestion around the ladder exit point on the upper deck begins at around 35 s into simulation. It reaches its peak level of congestion at around 146 s into the simulation, at which point there are on average 49 agents queuing to exit, and is not dissipated until 311 s into the simulation. A similar situation occurs on the middle deck, where exiting agents must transfer to the other ladder. In this case congestion starts at around 45 s, builds up to a peak at around 177 s, at which point there are 25 agents queuing to exit, and is not dissipated until 376 s into the simulation. The congestion is caused by only having a single means of escape, which also has a relatively poor flow capacity.

The negligible reduction in overall evacuation time, despite the 50% reduction in response times, is due to severe congestion which develops around the only means of exit: the single ladder. The significant level of congestion experienced by the slipform workers negates any improvement gained by the workers reacting more quickly. It is suggested that the time to clear the slipform and hence the overall building evacuation time could be improved if the flow capacity of the exit route was improved.

Key Finding 10.2: Impact on evacuation times of a global reduction in worker response times – For high-rise construction sites of up to 22 levels, halving the response time for all 525 workers results in a 33% decrease in the average total evacuation time for the workers in the main building. However, the overall evacuation time for the entire building is only decreased by 1%. The modest decrease in overall evacuation time for the entire building is due to the congestion experienced by workers in the formworks attempting to use the sole means of escape, a single ladder.

While achieving a 50% reduction in all the building occupant's response times may be difficult to achieve in practice, it can result in a significant (one-third) reduction in evacuation times for the main building population. However, the time required to clear the formworks and the overall evacuation time for the construction site are constrained by the low flow capacity of the single means of escape from the formworks: a single ladder. It is suggested that the evacuation time for the entire construction site and the formworks could be improved by increasing the flow capacity of the exit route from the formworks. While not explored in this analysis, it is expected that the

reduction in total evacuation time for the main building will be less significant with increasing height of construction.

6.3 Impact of replacing ladders with stairs in the formworks

The second concept to be explored to improve overall evacuation performance involves replacing the ladders in the formworks with temporary scaffold stairs. In this analysis we assume that every ladder connection between decks is replaced by a dogleg temporary scaffold stair. However, there is still only one connection between the formworks and the exit stair located in the core. Furthermore, the stair (as the ladder) is discontinuous and can only be accessed from the upper deck.

Other scenarios are possible where, for example, only the exit route from the slipform is replaced by a temporary stair. However, in the scenarios presented here it is assumed that all the ladders are replaced by temporary scaffold stairs and so the results are expected to be optimal.

6.3.1 Time to clear the slipform – impact of replacing ladders with temporary stairs in high-rise construction

Clearly, the time required to clear the slipform is not impacted by the height of construction, and therefore only BMS1 is considered. Presented in Figure 147 are the slipform exit curves for BMS1 and the corresponding case with the ladders replaced by temporary scaffold stairs. As can be seen, there is a considerable improvement in the exiting time for workers in the slipform. Presented in Table 52 are key exiting times from the slipform for both cases. The time to clear the slipform has decreased from 387 s (6 min 27 sec) to 320 s (5 min 20 sec), a decrease of 17% (67 s). The slipform is cleared more than 1 minute quicker using temporary scaffold stairs.

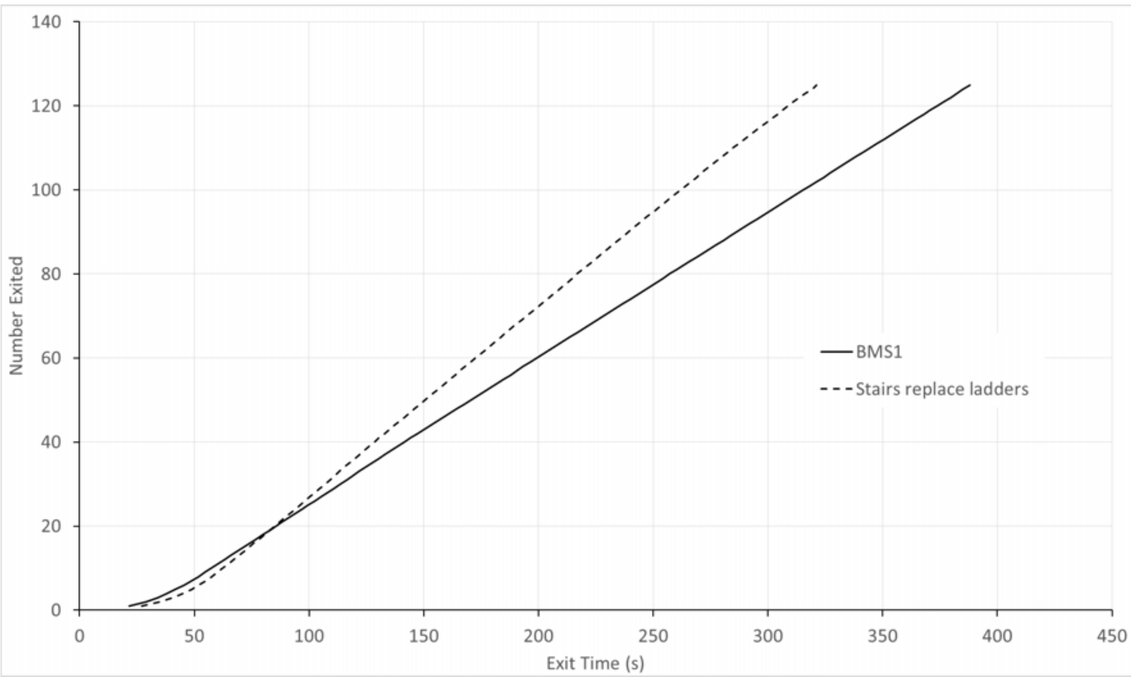


Figure 147. The average buildingEXODUS predicted slipform exit curves for BMS1 and BMS1 with stairs replacing ladders.

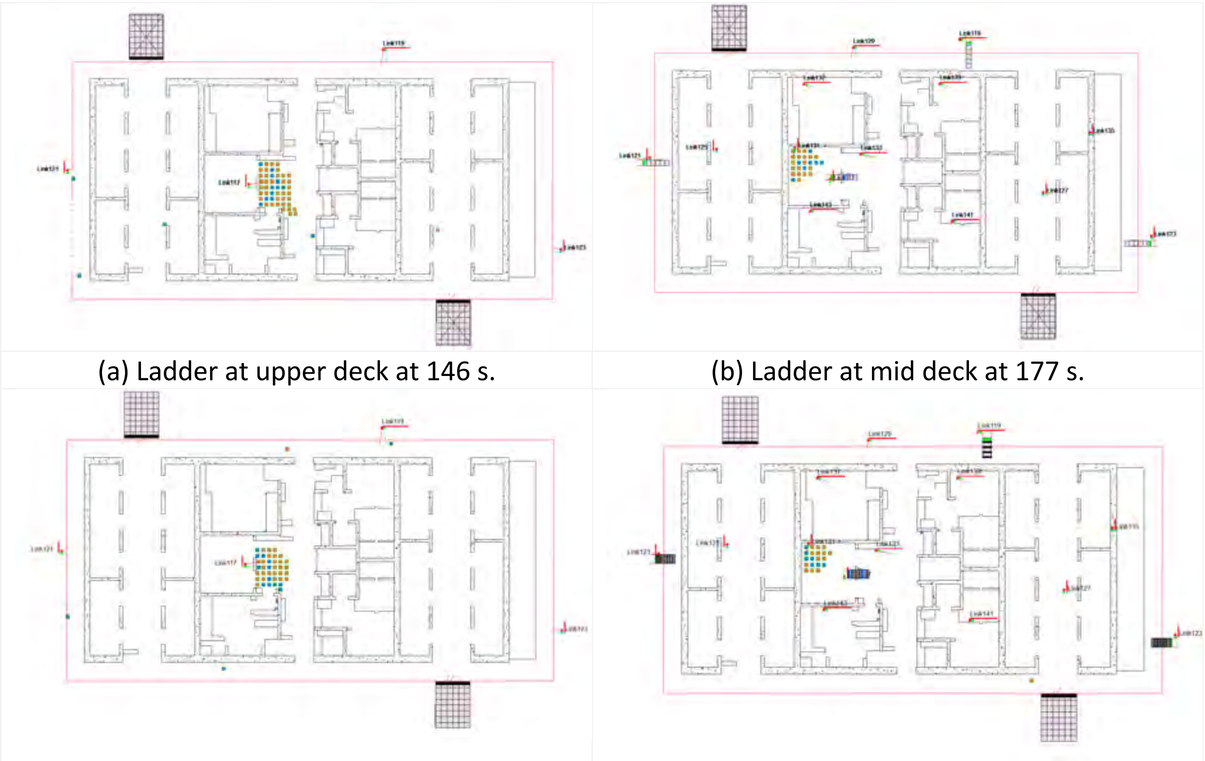
Table 52. Predicted (average values) times to exit the slipform for BMS1 and with stairs replacing ladders.

Scenario	1st	50%	75%	90%	98%	100%	Mean

	(1)*	(63)	(94)	(113)	(123)	(125)	
BMS1 (s)	22.5	208	298	352	381	387	208
With stairs (s)	26.7	178	248	291	316	320	178

* Figures in brackets represent number of agents exited.

The temporary scaffold dogleg stair has a greater flow capacity than the ladder, enabling it to reduce the severe congestion formed in the slipform around the entrance to the exit point. With the scaffold stairs replacing the ladder, the congestion at the entrance to the exit stairs lasts for a shorter duration and involves fewer agents. In particular, when using the temporary stair, the congestion starts later, ends sooner and involves fewer agents at its peak (see Figure 148 and Table 53). However, while the congestion has decreased, it is still present (see Figure 148 and Table 53), delaying the evacuation of the workers in the slipform. This suggests that either a second exit point or an exit with greater flow capacity, such as dual-lane temporary stair, is required to clear the congestion.



(a) Ladder at upper deck at 146 s.

(b) Ladder at mid deck at 177 s.

(c) Stair at upper deck at 151 s.

(d) Stair at mid deck at 308 s.

Figure 148. Peak congestion experienced on the upper and middle decks of the slipform.

Table 53. Congestion at the entrance to ladder/stair with number of agents involved at the most severe period.

	Upper deck				Middle deck			
	Start time (s)	Most severe (s)	End time (s)	No. of agents	Start time (s)	Most severe (s)	End time (s)	No. of agents
Ladders	35	146	311	49	45	177	376	25
Stairs	70	151	263	39	71	308	311	20

6.3.2 Impact of replacing ladders with temporary stairs within the slipform on total evacuation time in high-rise construction

Presented in Figure 149 are the building exit curves for BMS1 and BMS2 along with the corresponding cases with the ladders replaced by temporary scaffold stairs. As can be seen, there is a considerable improvement in the exiting time for the buildings in BMS1 and BMS2. Presented in Table 54 are key building exiting times for both BMS cases. As can be seen, for BMS1 the total building evacuation time has decreased from 613 s (10 min 13 sec) to 562 s (9 min 21 sec), a decrease of 8% (51 s). The building is cleared almost 1 minute quicker using temporary scaffold stairs in the slipform. For BMS2 the total building evacuation time has decreased from 852 s (14 min 12 sec) to 797 s (13 min 17 sec), a decrease of 6% (55 s). The building is cleared almost 1 minute quicker using temporary scaffold stairs in the slipform.

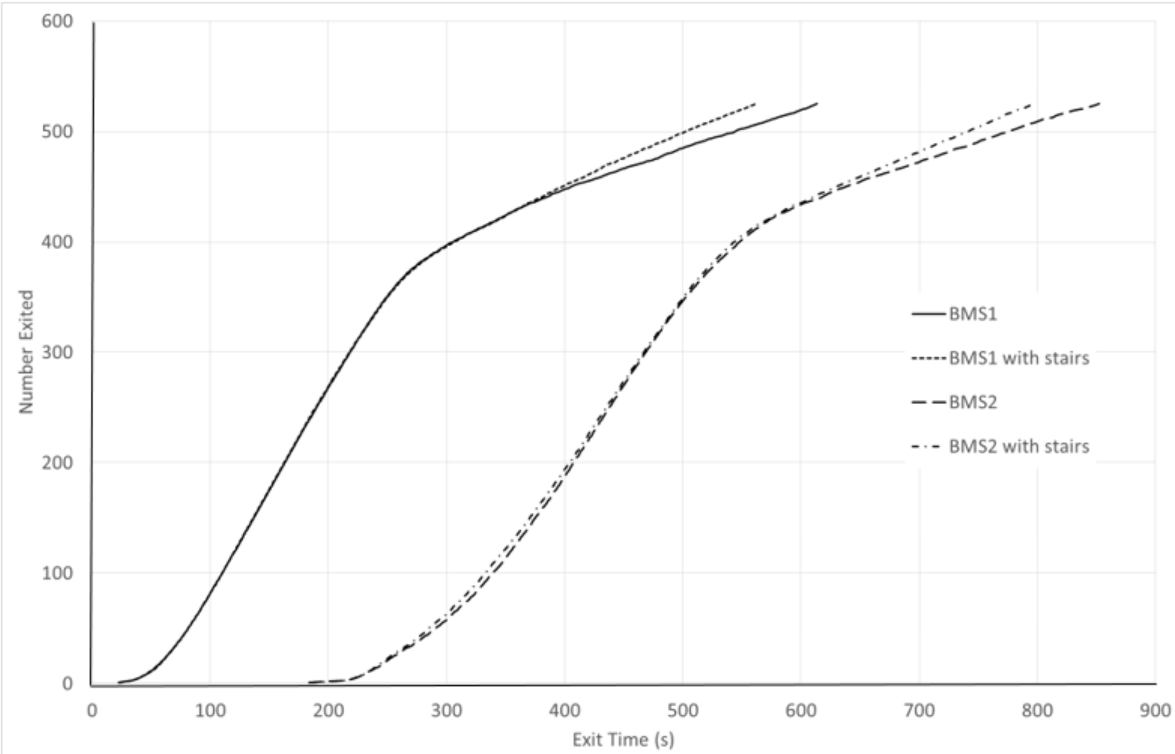


Figure 149. The average buildingEXODUS predicted building exit curves for BMS1, BMS2 and the corresponding cases with stairs replacing ladders.

Table 54. Predicted (average values) times to exit the building for BMS1, BMS2 and the corresponding cases with stairs replacing ladders.

Scenario	90% (473)*	95% (499)	98% (515)	100% (525)
BMS1 (s)	469	542	587	613
BMS1 with stairs (s)	444	500	538	562
BMS2 (s)	701	772	818	852
BMS2 with stairs (s)	681	738	773	797

* Figures in brackets represent number of agents exited.

Key Finding 10.3: Impact on evacuation times of replacing formwork ladders with temporary stairs – Replacing the ladders in the formworks with temporary scaffold dogleg stairs reduces the time required to clear the formworks by 17% (67 s) when occupied by 125 agents. While this is a

considerable reduction in the time required to clear the formworks, there is considerable congestion at the head of the temporary stair. The time required to clear the formworks could be decreased further if the flow capacity of the exit route from the formworks was increased. This could be achieved through adding another exit route or if the single-lane stair could be replaced with a dual-lane stair. As the last agents to leave the building are from the formworks, the reduction in time required to clear the formworks also decreases the overall building evacuation time. For construction sites of up to 22 levels, the overall building evacuation time is decreased by 8% (51 s), while for construction sites of 42 levels, the overall building evacuation time is decreased by 6% (55 s).

6.4 Impact of hoists on evacuation time

The third concept to be explored to improve overall evacuation performance involves utilising the hoists as a means of escape. There are many types of scenario that can be run using hoists involving variations in the number of hoists, hoist capacity, hoist performance (speed, acceleration, dwell times, door opening/closing times, etc.), hoist dispatch strategy employed and the proportion of workers who utilise the hoists. Furthermore, each of these parameters may have a different impact on the outcome of a scenario depending on the height of construction and number of occupants on site. It is thus not the intention of the analysis presented in this section to provide a definitive answer as to the advantage offered by using hoists for evacuation of construction sites, but to demonstrate how modelling can be used to explore the potential advantages of using a hoist evacuation strategy. Thus, only a limited number of indicative hoist scenarios are explored. It is further noted that the scenarios did not take into consideration the presence of fire or smoke.

All the hoist scenarios are compared with the two benchmark scenarios BMS1 and BMS2, which are both 100% stair-based evacuation scenarios. All population parameters used in the hoist scenarios are identical to those used in the benchmark scenarios. In the hoist scenarios we assume that all eight hoists within each scenario are identical.

6.4.1 Hoist dispatch scenario and configurations

To explore the impact of construction height on the use of hoists for evacuation, two benchmark scenarios are considered: BMS1 (22 levels) and BMS2 (42 levels). One hoist dispatch scenario is considered. It is not suggested that this is the optimal dispatch scenario but one of the possible ways in which the hoists can be used. The dispatch scenario involves each hoist servicing only a single floor. Each hoist travels between the ground level and its allocated level (see Table 55).

Table 55. Hoist dispatch scenario with the level number serviced by each hoist.

Hoist	BMS1 Level	BMS2 Level
Hoist Bank 1	2	21
Hoist Bank 2	4	23
Hoist Bank 3	6	25
Hoist Bank 4	8	27
Hoist Bank 5	10	29
Hoist Bank 6	11	31
North Lift Shaft	Slipform Mid Deck	Slipform Mid Deck
South Lift Shaft	Slipform Mid Deck	Slipform Mid Deck

When the hoist arrives on its targeted level, it opens its doors and waits until all the waiting passengers have boarded or the hoist has reached its capacity, at which point the doors close and the hoist descends to the ground level (Level 0). If there is an agent within 3 m of the hoist door, the hoist will assume that the agent is attempting to board the hoist and so will wait until the agent has boarded. As can be seen in Table 55, the hoists service every other floor level. Agents located on a level just above the level serviced by the hoist will travel down one level to use the hoist. Thus, the hoist services all occupants on the floor it services and the floor above. All of the agents located on core-only levels will travel down the temporary stairs to Level 11 (BMS1) or Level 31 (BMS2) to make use of the hoist at that level. Furthermore, in BMS2, the hoist on Level 21 services the agents of Levels 20, 21 and 22. All hoists start the simulation empty (no passengers) and all are initially located at Level 0.

Three hoist configurations are considered (see Table 41 for details).

a) Fast Hoist, capacity 40 (FH40). This assumes the characteristics of the Raxtar RX3245s.

b) Slow Hoist, capacity 40 (SH40). This assumes the characteristics of the Alimac Scando 650FC hoist with a capacity of 40.

c) Slow Hoist, capacity 30 (SH30). This assumes the characteristics of the Alimac Scando 650FC hoist with a capacity of 30.

Finally, two behaviour scenarios are considered. In the first scenario ALL the building population will make use of the hoists, with the exception of the agents on Levels 0 and 1 in BMS1. These agents walk down the stairs and exit the building. In the second scenario, 50% of the agents decide to wait for the hoists while 50% decide to use the stairs. Again in BMS1, all agents on Levels 0 and 1 use the stairs.

6.4.2 Hoist-only scenarios

There are two base scenarios involving hoists only, one corresponding to a relatively low height of construction, involving BMS1 (22 levels), and one corresponding to a relatively high height of construction, involving BMS2 (42 levels). Each base scenario involves four variant scenarios: the first variant scenario involves stairs only for comparison purposes, the second variant scenario involves the FH40 hoists (fast hoists with a capacity of 40), the third variant scenario involves the SH40 hoists (slow hoists with a capacity of 40) and the fourth variant scenario involves the SH30 hoists (slow hoist with a capacity of 30). As a result, in total there are eight scenarios, four for BMS1 (see Figure 150 and Table 56) and four for BMS2 (see Figure 151 and Table 58).

In the BMS1 scenarios, for the first 252 (48%) agents who evacuate, the stairs-only case provides a faster evacuation option than any of the hoist options. However, for all agents to evacuate, the hoist scenarios are faster than the stairs-only case, except for the SH30 scenario. The shortest average time for an agent to evacuate occurs in the scenario using the FH40 hoist, requiring 202 s which is 13% faster than the stairs-only case. The FH40 scenario also produces the shortest total evacuation time, 463 s or 25% faster than the stairs-only case. The SH30 case produces the longest total evacuation time, 845 s which is 37% slower than the stairs-only case, while the SH40 case produces a total evacuation time of 589 s which is only marginally (4%) faster than the stairs-only case (see Figure 150 and Table 56).

The average hoist statistics over 100 repeated simulations for each scenario are presented in Table 57. A trip is defined as a round journey, including the empty ascent from the ground and the loaded descent to the ground.

As can be seen in Table 57, the higher-capacity slow hoist (SH40) performs better than the lower-capacity slow hoist (SH30) as it can carry more agents, therefore making fewer journeys. On average, the higher-capacity hoists make 3.6 journeys per simulation and carry an average of 16.9 agents per trip, while the lower-capacity hoists make 3.9 journeys per simulation carrying an average of 14.2 agents per trip. This difference in performance becomes particularly important towards the end of the evacuation where the lower-capacity hoist must make an additional journey compared with the higher-capacity slow hoist for only one or two agents. This can be seen in Figure 150 by the tail end of the curves and in Table 57 where the last journey of the low-capacity hoist only carries on average 1.7 agents while the higher-capacity hoist carries seven agents.

Because of its greater speed and the relatively short travel distances involved in the BMS1 scenario, the fast FH40 hoists undertake more journeys on average to clear the building than the slower SH40 hoists. On average, the FH40 hoists undertake 4.4 journeys compared to the SH40 hoists, which undertake an average of 3.6. Furthermore, the FH40 hoists carry fewer agents on average than the SH40 hoists: 12.3 compared with 16.9 respectively. As suggested, this is due to a combination of the fast hoist speed and relatively short travel distance. This results in the FH40 hoists arriving at their first destination relatively quickly and before many of the agents have had a chance to respond. This is demonstrated by the average number of occupants the hoists pick up on their first journey: in the case of the FH40 this is 10.0 while in the case of the slower hoist this is 18.7 (see Table 57). Indeed, even in the case of the slow hoists, their first journey did not result in a hoist filled to capacity. This suggests that the total evacuation time for the building may be improved if there was a slight delay in the hoists starting their first journey OR if the hoists delayed leaving their targeted floor until they were filled to capacity. In reality, it is unlikely that the hoists would commence their involvement in the evacuation at the sounding of the alarm – there is likely to be some delay in the hoists starting to be used for evacuation – and so it is possible that the predicted initial inefficiency would not occur.

Key Finding 10.4: Impact on evacuation times of hoists for low construction – For relatively low high-rise construction (of up to 22 levels), the use of slow hoists of low capacity (30 people) extends the overall evacuation time by some 37% when compared to the stairs-only case. Increasing the capacity of the slow hoist (40 people) improves the overall performance of the hoist evacuation to the point that it is marginally faster (4%) than the stairs-only case. In contrast, the use of faster hoists with high capacity (40 people) reduces the overall evacuation time by 25% compared with the stairs-only case. However, the evacuation of only the last 50% of the building population is quicker than in the stairs-only case.

It is possible that small delays in engaging the hoists in evacuation activities may improve the overall predicted evacuation performance by increasing the number carried on the first hoist trips.

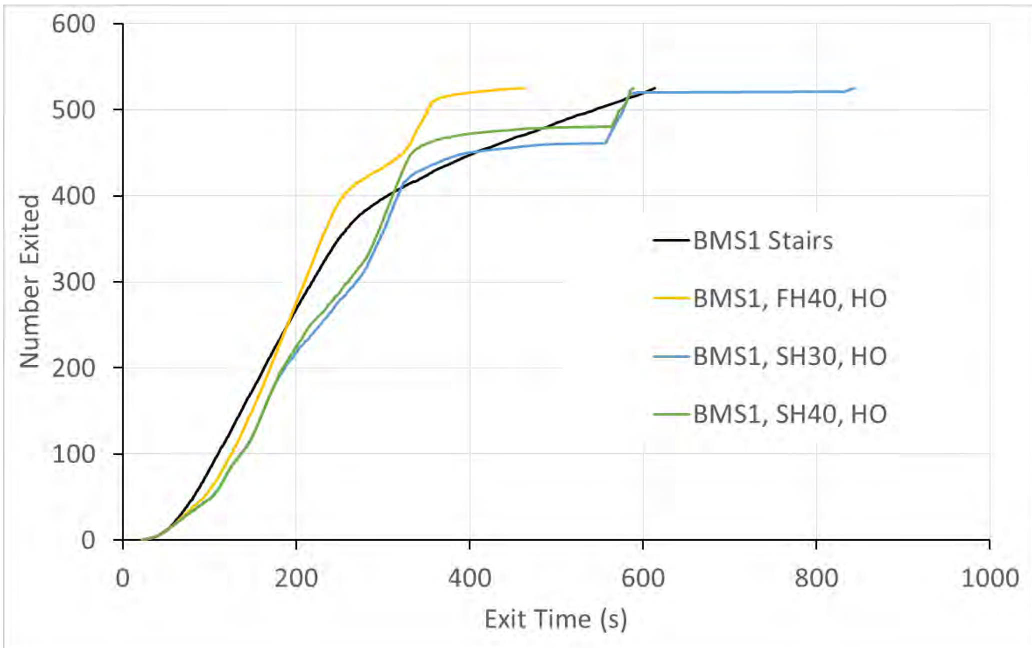


Figure 150. Predicted exit curves for hoist scenarios involving BMS1.

Table 56. Predicted exit times for BMS1 and three BMS1-based hoist scenarios (100% using hoists).

Scenario	Mean	50% (263)*	75% (394)	90% (473)	95% (499)	98% (515)	100% (525)
BMS1 stairs only (s)	232	198	297	469	542	587	615
SH30 (s)	263	239	315	563	578	583	845
SH40 (s)	248	230	309	420	572	583	589
FH40 (s)	202	195	251	338	351	374	463

* Figures in brackets represent number of agents exited.

Table 57. Average hoist trip data for BMS1 hoist-only scenarios.

Scenario	Average total # of hoist trips	Average # of trips per hoist	Average # of agents per hoist trip	Average # of agents on first hoist trip	Average # of agents on last hoist trip
BMS1 HO Fast 40	35.5	4.4	12.3	10.0	1.8
BMS1 HO Slow 40	28.9	3.6	16.9	18.7	7.0
BMS1 HO Slow 30	31.1	3.9	14.2	16.7	1.7

In the BMS2 scenarios, where the building height is increased to 42 levels, the disadvantage of the slower hoists becomes more pronounced. This is because the hoists have a greater distance to travel and the agents spend more time waiting. As in the lower high-rise BMS1 case, the higher-capacity slow hoist (SH40) performs better than the lower-capacity slow hoist (SH30), but the difference in performance between the two slow hoists becomes more pronounced. The SH30 case (slow hoist with a capacity of 30) produces the longest total evacuation time, 1,530 s or 80% slower than the stairs-only case, while the SH40 case (slow hoist with a capacity of 40) produces a total evacuation time of 1,078 s, which is 27% slower than the stairs-only case.

Of the three BMS2 hoist-only scenarios, only the high-capacity fast hoist (FH40) offers an advantage over the stairs-only case, producing a total evacuation time of 592 s, which is 31% faster than the stairs-only case. Furthermore, unlike in the low high-rise BMS1 case, the FH40 hoist evacuation outperforms the stairs-only case throughout the entire evacuation.

As in the BMS1 scenarios, the fast FH40 hoists undertake more journeys than the slower SH40 hoist with similar capacity. On average the FH40 hoists undertake 2.5 journeys per scenario carrying an average of 24.2 agents per journey compared to 2.1 journeys carrying 28.8 agents for the SH40 hoists. However, in the case of the higher building, all the hoists make fewer journeys and carry a greater number of agents per trip compared with the corresponding hoists in the case of a lower building (see Table 57 and Table 59). This suggests that as the building height increases, the hoists become more efficient, making fewer trips and carrying more occupants per trip. The greater distance travelled by the hoists also means that it takes longer to reach their targeted destination, and so more agents are available for the first trip. As a result, the hoists carry considerably more agents on their first trip in the higher building case than in the lower building case. We note that the number carried in the first trip is close to capacity and so close to optimal (see Table 59).

Key Finding 10.5: Impact on evacuation times of hoists for high construction – As the height of construction is increased (up to 42 levels), the use of slow hoists, regardless of capacity (occupancy of 30 or 40), becomes increasingly inefficient, extending the overall evacuation time by between 27% and 80% depending on capacity, compared with the stairs-only case. However, the use of faster hoists with high capacity (40 occupancy) reduces the overall evacuation time by 31% compared with the stairs-only case. As the height of construction increases, the number of hoist journeys decreases, with each hoist journey carrying more agents.

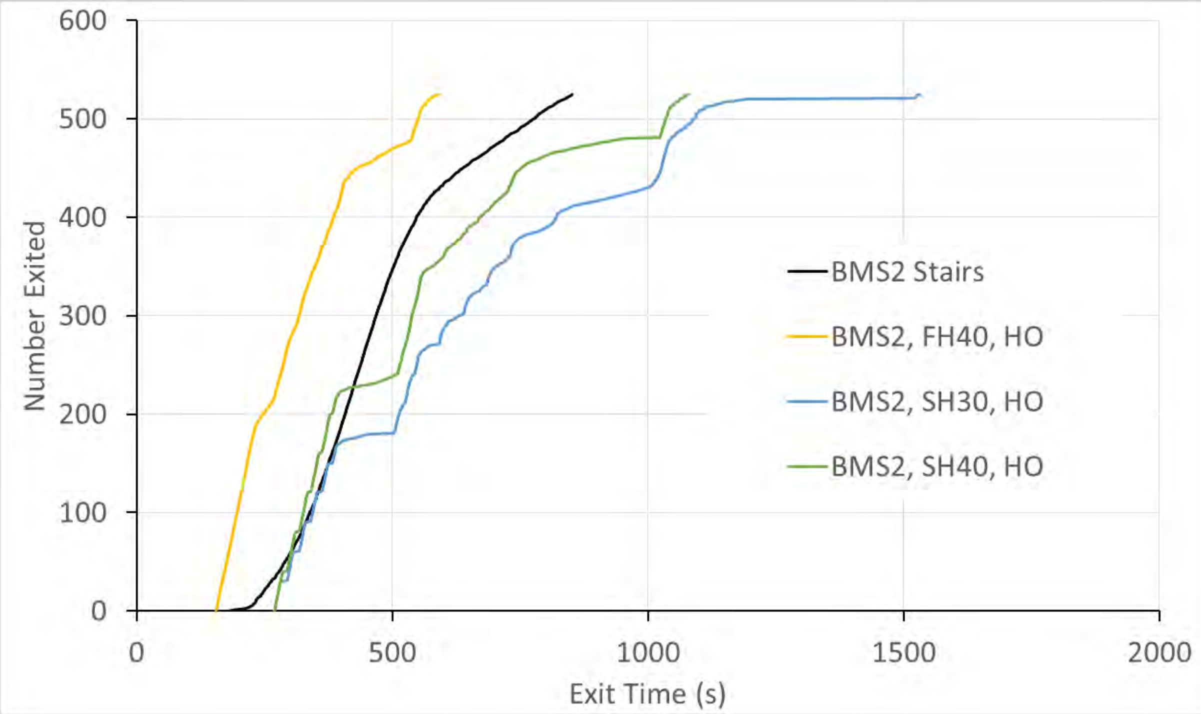


Figure 151. Predicted exit curves for hoist scenarios involving BMS2.

Table 58. Predicted exit times for BMS2 and three BMS2-based hoist scenarios (100% using hoists).

Scenario	Mean	50% (263)*	75% (394)	90% (473)	95% (499)	98% (515)	100% (525)
BMS2 stairs only (s)	468	446	543	703	772	821	852
SH30 (s)	623	558	813	1,039	1,087	1,145	1,530
SH40 (s)	533	521	662	894	1,033	1,054	1,078
FH40 (s)	310	293	381	523	549	566	592

* Figures in brackets represent number of agents exited.

Table 59. Average hoist trip data for BMS2 hoist-only scenarios.

Scenario	Average total # of hoist trips	Average # of trips per hoist	Average # of agents per hoist trip	Average # of agents on first hoist trip	Average # of agents on last hoist trip
BMS2 HO Fast 40	19.8	2.5	24.2	35.3	8.8
BMS2 HO Slow 40	16.5	2.1	28.8	38.7	16.6
BMS2 HO Slow 30	21.6	2.7	22.8	29.7	9.0

It is noted in Figure 150 and Figure 151 that there are a number of plateaus in the exit curves for the slower hoists. This is due to the relatively slow speed of the hoists. In Figure 151 (BMS2 case), the first plateau starts at around 390 s and ends at around 500 s. These occur after the first hoist cycle. The bank of six hoists have made their first journey up and returned at intervals and emptied their loads on the ground level and started their second journey up. From around 390 s to around 500 s there are no hoists on the ground level, with the bank of six hoists going up for their second journey or the two hoists that have been dispatched to the top of the building (and hence with the greatest travel distance) still coming down from their first journey. As a result, there is virtually no one on the ground level exiting the building during this period, thereby creating the long plateau until the second batch of two hoists arrive. In the case of the faster hoists, the cycles are not so prominent, resulting in at least one hoist being on the ground emptying its load virtually throughout the simulation. In the case of the lower-capacity slow hoist, following the last plateau, the last hoist journey only carries on average four agents. This last trip stretches the total evacuation time from 1,190 s to 1,530 s.

6.4.3 Hoist and stair scenarios

In these scenarios every agent has a 50% chance of deciding to make use of the stairs or the hoists. The actual number of agents using either the stairs or the hoists is not set within each simulation, but determined by a random process. Thus, within each simulation approximately 50% will use the stairs and 50% will use the hoists, but this number can vary slightly depending on random chance. Furthermore, once an agent has decided to use the stairs or the hoists, they will not change their mind. For instance, agents who decide to use the hoists will wait for the hoist regardless of how long it takes.

As in the hoist-only scenarios discussed in Section 6.4.2, there are two base scenarios involving the hoist and stair scenarios, one corresponding to a relatively low height of construction, involving BMS1 (22 levels), and the other corresponding to a relatively high height of construction, involving BMS2 (42 levels). Also as in the hoist-only scenarios, each base scenario involves four variant scenarios: the first variant scenario involves stairs only for comparison purposes, the second variant scenario involves the FH40 hoists (fast hoists with a capacity of 40), the third variant scenario involves the SH40 hoists (slow hoists with a capacity of 40) and the fourth variant scenario involves the SH30 hoists (slow hoist with a capacity of 30). As a result, in total there are eight scenarios: four for BMS1 (see Figure 152 and Table 60) and four for BMS2 (see Figure 153 and Table 62).

When 50% of the population attempt to use the stairs, the use of hoists in BMS1 (22 levels) becomes more efficient. In this case, all the scenarios involving hoists are quicker than the stairs-only scenario. The fastest evacuation occurs for the case with the fastest hoists. The FH40 scenario produces the shortest total evacuation time: 471 s or 23% faster than the stairs-only case. It is noted that this evacuation time is only marginally slower than the time achieved by the same hoists when 100% of the agents used the hoists (i.e. in that case the hoists were 25% faster than the stairs-only case). However, when 50% of the agents use the stairs, none of them are disadvantaged, i.e. all the agents exit the building in a time that is either equal to or less than that in the stairs-only case. If the slower SH40 or SH30 hoists are used, the overall evacuation time is reduced by 7.6%, regardless of the capacity of the hoists (see Figure 152 and Table 60).

The average hoist statistics for each scenario are presented in Table 61. As can be seen in Table 61, both of the slower hoists achieve similar performance regardless of capacity. The slow hoist with low capacity (SH30) and slow hoist with high capacity (SH40) both undertake 3.3 journeys on average with the higher-capacity hoist carrying 7.9 passengers on average compared with 9.5 passengers for the lower-capacity hoist. Both average passenger loads are well below the maximum capacity for each hoist. This is because half the building population has decided to use the stairs rather than wait for a hoist and thus the numbers wanting to use the hoist have greatly decreased and are not constrained by the carrying capacity of the hoists. Furthermore, from Table 61 we note that the fastest hoist (FH40) is the most inefficient, undertaking an average of 4.1 journeys and carrying an average of only 6.0 passengers per trip. This is due to the same issue as highlighted previously, i.e. the higher speed of the hoist results in fewer agents ready for the first trip (note that only 4.5 passengers are carried by the hoist on its first trip).

Key Finding 10.6: Impact on evacuation times of hoists when 50% of the population use hoists for low construction – For relatively low high-rise construction sites (up to 22 levels), if half the population use the stairs during the evacuation, hoists can speed up the evacuation of the construction site relative to the stairs-only case, regardless of the speed and capacity of the hoists.

Given the high number of agents using the stairs (50%), the capacity of the hoists is no longer a constraint on hoist performance.

The use of fast hoists with high capacity (40 people) reduces the overall evacuation time by 23% compared to the stairs-only case. This improvement in evacuation performance is only 2% (8 s) slower than the case in which 100% of the agents use the hoists. Furthermore, when only 50% of the agents use the hoists, unlike in the case when 100% use the hoists, the entire population exits the building in a shorter time than if they all used the stairs. As a result, the evacuation is more efficient when 50% of the population use the hoists. Even if the slower hoists are utilised, this results in a 7.6% improvement in evacuation time, regardless of the capacity of the hoists.

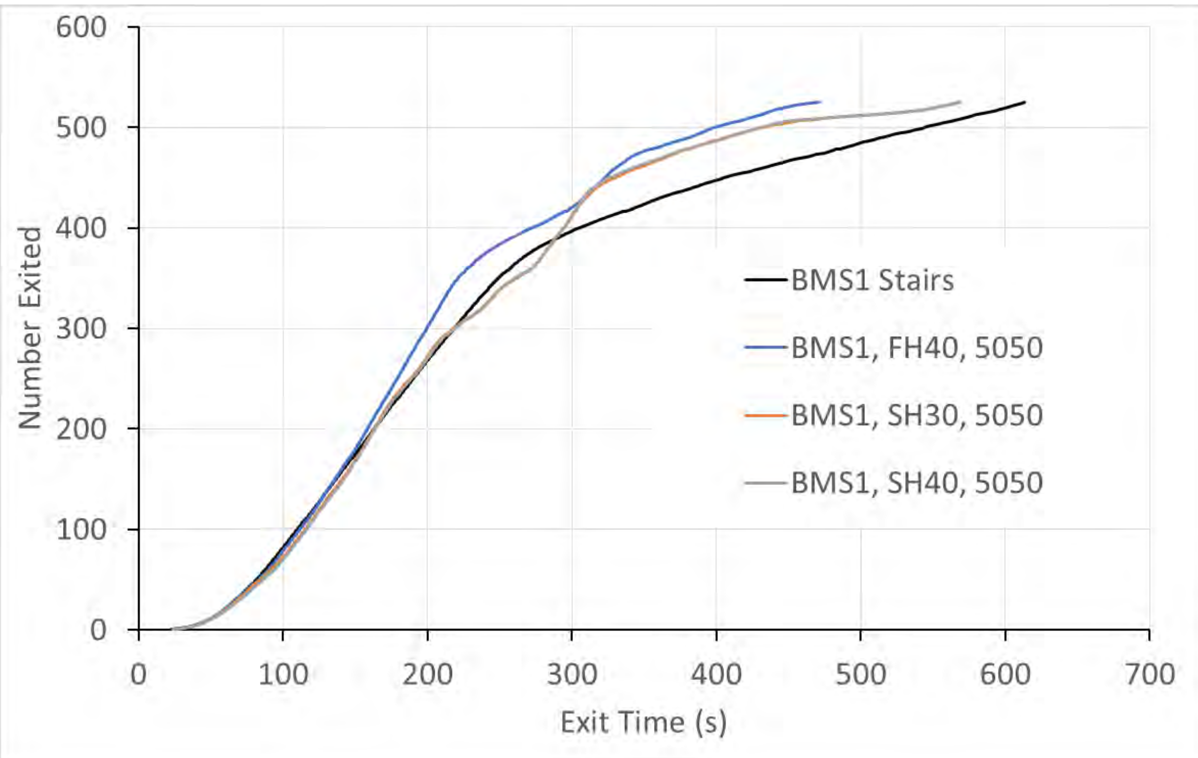


Figure 152. Predicted exit curves for hoist and stair scenarios involving BMS1.

Table 60. Predicted exit times for BMS1 and three BMS1-based hoist scenarios (50% using hoists).

Scenario	Mean	50% (263)	75% (394)	90% (473)	95% (499)	98% (515)	100% (525)
BMS1 stairs only(s)	232	198	297	469	542	587	615
SH30 (s)	217	196	292	372	427	534	568
SH40 (s)	217	197	291	370	428	535	570
FH40 (s)	201	184	265	346	396	436	471

Table 61. Average hoist trip data for BMS1 hoist and stair scenarios.

Scenario	Average total # of hoist trips	Average # of trips per hoist	Average # of agents per hoist trip	Average # of agents on first hoist trip	Average # of agents on last hoist trip
BMS1 5050 Fast 40	32.8	4.1	6.0	4.5	1.6
BMS1 5050 Slow 40	26.7	3.3	7.9	10.0	2.7
BMS1 5050 Slow 30	26.8	3.3	9.5	9.6	5.1

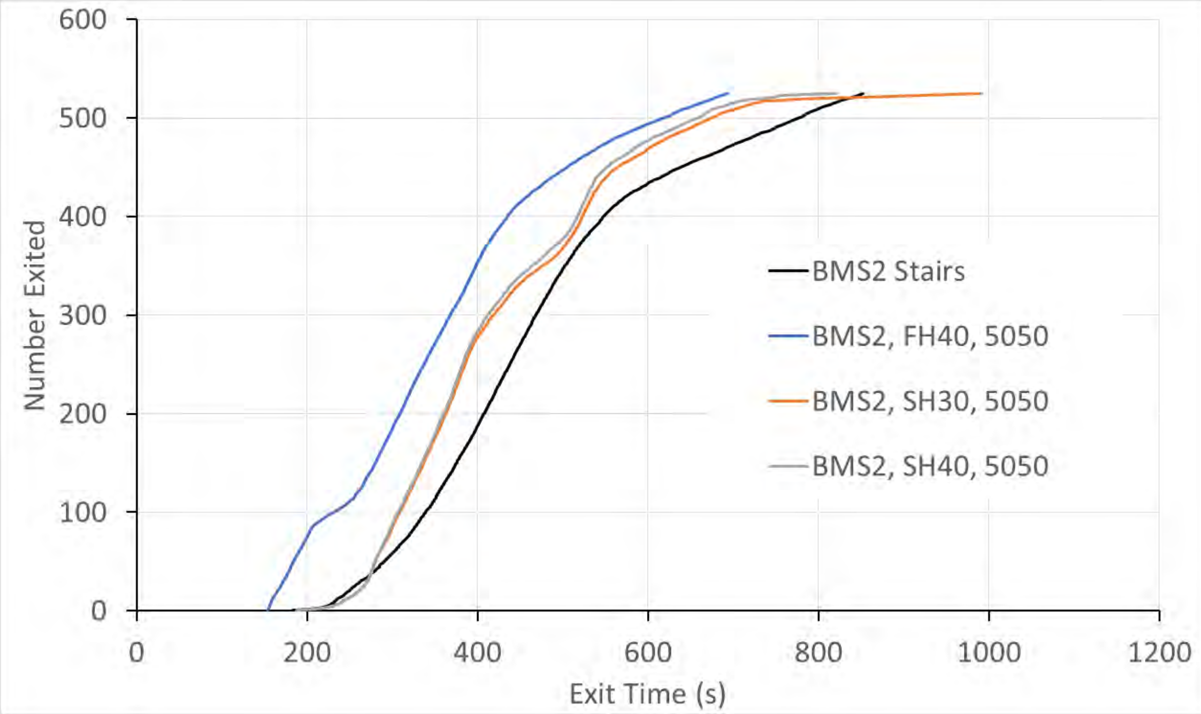


Figure 153. Predicted exit curves for hoist and stair scenarios involving BMS2.

Table 62. Predicted exit times for BMS2 and three BMS2-based hoist scenarios (50% using hoists).

Scenario	Mean	50% (263)*	75% (394)	90% (473)	95% (499)	98% (515)	100% (525)
BMS2 stairs only (s)	468	446	543	703	772	821	852
SH30 (s)	427	392	520	610	671	731	991
SH40 (s)	419	389	514	593	653	703	821
FH40 (s)	357	345	420	550	613	664	692

* Figures in brackets represent number of agents exited.

Table 63. Average hoist trip data for BMS2 hoist and stair scenarios.

Scenario	Average total # of hoist trips	Average # of trips per hoist	Average # of agents per hoist trip	Average # of agents on first hoist trip	Average # of agents on last hoist trip
BMS2 5050 Fast 40	19.0	2.4	11.6	17.6	3.4
BMS2 5050 Slow 40	13.0	1.7	16.6	27.1	6.1
BMS2 5050 Slow 30	14.0	1.8	16.5	25.6	7.5

In relatively high high-rise construction (BMS2, 42 levels), when 50% of the population use the stairs and 50% use the hoists, only the high-capacity hoists produce evacuation times quicker than utilising stairs only. The fastest evacuation occurs for the case with the fastest hoists. The FH40 scenario produces the shortest total evacuation time: 692 s or 19% faster than the stairs-only case. However, this is considerably slower than the case in which 100% of the agents use the hoists (592 s or 30% faster than the stairs-only case). If the slower SH40 hoists are used, the overall evacuation time is reduced by only 3.6%, while if the lower-capacity SH30 hoists are used, the overall evacuation time increases by 16.3% (see Figure 153 and Table 62).

The high-capacity slow hoists undertake fewer trips on average than the low-capacity slow hoists (1.7 compared with 1.8 respectively) and carry more passengers per trip (16.6 compared with 16.5 respectively). On average, the first trip of the high-capacity hoists carries 27.1 passengers compared to 25.6 passengers for the low-capacity hoists. This suggests that some of the high-capacity hoists may be carrying in excess of 30 passengers on a number of trips. This is confirmed by investigation of the detailed hoist usage statistics. For example, the hoist in the South Lift Shaft which services the slipform has 61% of its first journeys carrying more than 30 passengers. Furthermore, in 90% of the 100 repeated simulations, the hoists servicing the slipform in the SH30 scenario need to make two trips, while in the SH40 scenario, only 26% of the simulations require a second trip. This is necessary as the SH30 hoists were unable to carry more passengers on their first trip due to their reduced capacity. This is significant, since in the BMS2 case, the slipform workers are usually the last to exit the building and so the exit times for these agents dictates the overall evacuation time for the building. Thus, the extra trips that the hoists servicing the slipform have to make due to the lower capacity result in a large increase in the overall evacuation time. This observation is also supported by the times required to evacuate 98% and 100% of the building. Although the lower-capacity slow hoists scenario is some 90 s faster than the stairs-only case to evacuate 98% of the building, it is 139 s slower than the latter to evacuate 100% of the building (see Table 62).

On average the FH40 hoists undertake 2.4 journeys per simulation, carrying an average of 11.6 agents per journey, compared to 1.7 journeys carrying 16.6 agents for the slower high-capacity hoists (SH40). As observed previously, the greater speed of the hoists means that it can undertake more journeys than the slower hoist, and as it arrives sooner at its target destination, there are fewer agents ready to take the hoist. This is demonstrated by the lower number of agents utilising the faster hoist on the first trip, i.e. 17.6 for FH40 compared with 27.1 for SH40 (see Table 63).

Key Finding 10.7: Impact on evacuation times of hoists when 50% of the population use hoists for high construction – In situations where half the population make use of stairs and half the population make use of hoists, the efficiency of using hoists decreases with increasing building height, regardless of the speed or capacity of the hoists. However, the use of fast hoists with high capacity (40 persons) can reduce the total evacuation time by 19% compared to the stairs-only case while the use of slow hoists with high capacity (40 persons) can reduce the total evacuation time by 3.6%. The use of slow hoists with low capacity (30 persons) can increase the total evacuation time by 16.3%.

6.4.4 Summary of hoist impact on evacuation

The use of hoists for evacuation is extremely complex and dependent on a number of factors. In this analysis only a small subset of parameters were investigated and so the results cannot be generalised to cover all possible or likely situations. It is further noted that the scenarios did not take into consideration the presence of fire or smoke. It is essential that a detailed analysis is undertaken for the specific application before the potential benefit of using hoists can be established. For the cases examined here, depending on the specific combination of parameters examined, the use of hoists could reduce the evacuation time by as much as 30% or increase the evacuation time by as much as 80%.

One of the key parameters that must be considered is the strategy for deploying the hoists. In the cases examined here, a simple hoist dispatch strategy was employed. The hoists would visit a specific target floor and only operate between the ground level and the target level until all occupants from the target level were evacuated. In the cases examined, there were a total of eight hoists, with six hoists dispatched to every other completed or near completed floor level and two hoists dispatched to the slipform. For the imposed dispatch strategy, the scenario parameters considered were hoist performance (fast/slow), hoist capacity (40/30), building height (22/42 levels) and the proportion of the population that used the hoist for evacuation (0%, 50% and 100%).

Presented in Table 64 is a summary of the evacuation performance, assuming there were 525 workers on site, with 125 located in the formworks.

Table 64. Summary of hoist evacuation performance.

Fast Hoists with High Capacity (FH40)			
Height of Construction	**Stairs Only**	**Hoist Only**	**50/50 Stairs/Hoist**
22 Levels	**615 s**	**25% (463 s)**	**23% (471 s)**
42 Levels	**852 s**	**30% (592 s)**	**19% (692 s)**
Slow Hoists with High Capacity (SH40)			
Height of construction	**Stairs Only**	**Hoist Only**	**50/50 Stairs/Hoist**
22 Levels	**615 s**	**4% (589 s)**	**7% (570 s)**
42 Levels	**852 s**	**-26% (1,078 s)**	**4% (821 s)**
Slow Hoists with Low Capacity (SH30)			
Height of construction	**Stairs Only**	**Hoist Only**	**50/50 Stairs/Hoist**
22 Levels	**615 s**	**-37% (845 s)**	**8% (568 s)**
42 Levels	**852 s**	**-80% (1,530 s)**	**-16% (991 s)**

The performance of the hoist can be summarised as follows:

- ***only when fast hoists with high capacity are used will the evacuation be faster than the stairs-only case for both low and high construction height and if hoists are used by 50% and 100% of the building population***
  - ***when slower hoists with high capacity are used, the evacuation performance is greatly reduced in all cases***
  - ***when slower hoists with low capacity are used, the evacuation performance is reduced even further in all cases***
- ***the most efficient way to use fast high-capacity hoists is to ensure that as many of the building population use the hoists as possible***
  - ***a 30% reduction in overall evacuation time is possible compared to stairs only if 100% of the occupants use the hoists***
  - ***evacuation efficiency increases with height of construction if 100% of the population use the hoists***
  - ***if 50% of the population use the hoists, evacuation times increase compared to the 100% hoist usage performance, but this is still at least 19% quicker than using the stairs only***
- ***if slow high-capacity hoists are used, the best performance is achieved when 50% of the occupants use the hoists***
  - ***a reduction in evacuation time of 7% is achieved for low construction and 4% for high construction. Thus, the performance of the slow high-capacity hoist decreases with construction height***

- ***100% usage of slow high-capacity hoists should be avoided for high construction as this results in a significant decrease in evacuation performance***

- ***if slow low-capacity hoists are used, the only benefit in evacuation performance is achieved for low construction and if 50% of the population make use of the stairs. The best performance that can be achieved is an 8% reduction in evacuation performance. In all other cases the use of slow low-capacity hoists results in a reduction in evacuation performance.***

6.5 Summary of the main results

In this section the validated evacuation simulation software and data-sets were used to explore potential improvements to evacuation procedures on high-rise construction sites. In particular, the analysis explored the impact of the following scenarios:

- **Reduction in response time of workers**

For high-rise construction of up to 22 levels, decreasing the response time of ALL 525 workers, including the 125 workers located in the formworks, by 50% results in an average decrease of 33% in the total evacuation time for workers in the main building. However, the evacuation time for the entire building, which is driven by the evacuation time for workers located in the formworks, is only decreased by 1%. The modest decrease in overall evacuation time is a result of the limited means of egress from the slipform, which was limited to a single ladder. While achieving a 50% reduction in everyone's response time may be difficult to achieve in practice, it can result in reducing evacuation times for the main building population by a third.

- **Replacing ladders with temporary stairs in the formwork**

The overall evacuation time for the high-rise construction site consisting of 525 workers is governed by the time for the 125 workers located in the formworks to clear the formworks. This in turn is impacted by the severe congestion that occurs at the entrance point of the only exit from the formworks, a single ladder. Replacing the ladders in the formworks with temporary scaffold dogleg stairs reduces the time required to clear the formworks by 17% (67 s). As the last worker to leave the building is from the formworks, this also decreases the overall building evacuation time. For a high-rise construction of up to 22 levels, the overall building evacuation time is decreased by 8% (51 s), while for high-rise construction of up to 42 levels, the total building evacuation time is decreased by 6% (55 s). While replacing the single ladder exit route with a single temporary stair results in an appreciable reduction in the time required to clear the formworks, considerable congestion remains at the head of the temporary stair. Thus, the time required to clear the formworks could be decreased further if the flow capacity of the exit route from the formworks could be increased by, for example, the addition of a second exit route or if the single-lane stair was replaced with a dual-lane stair.

- **Using hoists to assist in evacuation**

The use of hoists for evacuation is extremely complex and dependent on a number of factors including the number of available hoists (eight in the case examined), hoist dispatch strategy (each hoist ferrying occupants between a targeted floor (every other floor) and ground), hoist performance (fast/slow), hoist capacity (40/30), building height (22/42 levels) and the proportion of the population that use the hoist for evacuation (0%, 50% and 100%). It is further noted that the scenarios did not take into consideration the presence of fire or smoke. It is thus difficult to generalise to accommodate all possible or likely situations.

The most efficient evacuation was achieved using fast high-capacity hoists. Using these hoists, it was noted that:

- for both low (22 levels) and high (42 levels) high-rise construction and whether 100% or 50% of the population made use of the hoists, the use of hoists resulted in at least a 19% improvement in total evacuation time over the stairs-only case

- overall evacuation times could be reduced by 30% compared to stairs only if 100% of the occupants use the hoists
- evacuation efficiency increases with construction height if 100% of the population use hoists
- if 50% of the population use the hoists, evacuation times increase compared to the 100% hoist usage performance, but this is still at least 19% quicker than using the stairs-only case***.***

In the worst case, the use of slower low-capacity hoists resulted in the poorest performance, almost always resulting in significantly longer evacuation times compared to the use of stairs only. For high high-rise construction sites (up to 42 levels), if 100% of the occupants used hoists for evacuation this could increase evacuation times by 80% compared to the stairs-only case. If 50% of the population used hoists, evacuation times were increased by 16%.

The conclusion of this section marks the successful completion of project Task 5 addressing the requirements of project Objective 5.

7 Key findings

The analysis of the trial data and subsequent modelling analysis have been described in Sections 4 to 6. Presented in Table 33 is a summary of the main evacuation results from the four full-scale unannounced trials. The average response times for workers in the formworks varied from 29 s to 58 s, while the average response time for workers in the main building varied from 62 s to 76 s. Total evacuation times varied from 9 m 14 s to 20 m 47 s, depending on height of construction and number of workers, with exit flows (excluding Trial 2) varying from 0.29 p/s to 0.32 p/s, with a weighted mean exit flow of 0.29 p/s.

Throughout the analysis of the collected experimental data and evacuation simulations, 60 findings were highlighted of which 31 were considered key findings. The key findings are presented here and organised in topic categories.

(1) Questionnaire analysis:
The eight key findings concerning the questionnaire analysis were described in Section 4.5.

- **Survey demographics**

Key Finding 5.1: Correctly completed questionnaires were received from 7% (61 participants) of the population that evacuated during the four trials, with all the data being generated from Trial 1 and Trial 2. However, the data does represent information from 27% of the people who evacuated from these two trials. Concerning the demographics of the questionnaire participants:

- the majority (64%) were aged between 25 and 44 years of age with 25% over 44 years of age
- the majority of participants (61%) did not have English as their first language
- the majority of participants (75%) had been on the construction site for less than six months, with 20% having been on the site for less than one month.

These results suggest that the majority of the workforce are not native English speakers and given that 20% had been on the site for less than one month, that a sizeable number of workers may not be fully familiar with the workplace.

- **Response to alarm**

Key Finding 5.2: The majority of participants (62%) believed that the alarm was a real emergency, suggesting that the workers' response may be representative of how they would react in a real emergency. Furthermore, while not perfect, the volume of the alarm on the two sites appears to have been adequate given that 97% of the respondents reported hearing the alarm.

Key Finding 5.3: More than four-fifths (82%) of the participants knew that they were supposed to evacuate immediately on hearing the alarm but only half (49%) reported that their first action upon hearing the alarm was to start to evacuate. This result is supported by the video evidence which suggests that many of the workers delayed the start of their evacuation.

Key Finding 5.6: Four-fifths (80%) of the participants claim they were prompted by the alarm and did not require a staff intervention to commence their evacuation. This result is not supported by the video evidence which suggests that many of the workers delayed the start of their evacuation in order to complete their tasks, to shut down a task or to pack up equipment. Furthermore, the video evidence suggests that between 43% and 70% of the workers required a staff intervention to commence their evacuation.

One possible explanation for the difference between knowing the requirement and following through with the requirement, and with the need for supervisor intervention, is that it is not clear what is precisely meant by evacuate immediately. This suggests that better training and/or greater enforcement through supervisors is required.

- **Wayfinding**

Key Finding 5.4: A third of participants (33%) stated that they knew the exit route while a fifth (21%) stated that they looked for emergency exit signage, and very few simply followed others or looked for an authority figure to direct them. It is noted that there was no significant difference in exit route knowledge between native and non-native English speakers. However, there was a statistically significant difference in exit route knowledge between the two sites (22 BG is better than 100 BG), which may suggest that local site policy and procedures (safety culture) may influence workers' knowledge of evacuation procedures.

The high proportion of workers that relied on exit signage highlights the importance of having up-to-date and prominent emergency exit signage on site.

- **Task importance**

Key Finding 5.5: Workers perceive that employers find it more important than they do to complete their tasks prior to evacuating, suggesting improvements in local safety culture may be desirable. Furthermore, there was a statistically significant difference between trials, suggesting that the workers at 22 BG perceived a higher pressure to complete tasks than those at 100 BG. This may be related to the progress of work on both sites.

In addition, this perception may be sending mixed messages to the workers regarding the need for rapid evacuation, hence explaining the observation that while 82% of the workers understand the need to evacuate immediately only 49% did so (see Key Finding 5.3). This reinforces the suggestion of the need for better training and improvements in local safety culture.

- **Risk perception**

Key Finding 5.7: Construction site workers appear to have the same appetite for risk as the average person, i.e. they are not more inclined to take risks than the average person.

Key Finding 5.8: Construction site workers perceive that they are in a safe environment while on their construction site. Furthermore, there was a statistically significant difference in the level of safety perceived by workers on the Multiplex construction sites compared with their perception of safety on construction sites in general.

These results are somewhat surprising given that construction sites are inherently hazardous environments (with an average fatality rate four times that of land-based industries in general (see Section 1.1)). While the high level of perceived safety on Multiplex sites is a credit to the safety culture developed by Multiplex, if workers are not also aware of, and alert to, the inherent dangers of the construction site this may lead to a level of complacency in their response to potentially hazardous situations that may develop.

For example, while most workers believed that the alarm represented a 'real' emergency incident, they also felt that they were in 'no danger'. If we also take into consideration the workers' perception that their managers would prefer them to complete their tasks prior to evacuating, this may explain some of the long response times observed during the trials. One way of tackling this complacency is through training and developing an understanding of how quickly an emergency situation can deteriorate, reinforcing the message that it is essential to disengage immediately from pre-alarm activities when an alarm is sounded, and that it is important to know what immediately means – emphasising the point that, in an emergency, every second counts.

(2) Generalised response time (RT) analysis relating to the formworks:
The five key findings concerning the generalised response time distributions for the formworks were described in Section 4.6.

- **Nature of RT distribution for formworks**

Key Finding 6.1: The response times for workers in the formworks can be represented using a normal distribution.

This is different to the usual representation of response times which is lognormal in nature. This relationship has been observed for three different unannounced full-scale evacuation trials conducted on two different high-rise construction sites.

- **Impact of height on formworks RT distribution**

Key Finding 6.2: Two independent evacuation trials from two high-rise construction sites, with jumpforms at Levels 14 and 33, involving 28 and 32 workers respectively involved in similar activities just prior to a concrete pour, suggest that the response time distribution is not impacted by height.

This suggests that for high-rise construction sites with formworks located at up to 33 levels, the response times for workers located in the formworks are not impacted by the height of construction. This observation may be the result of construction workers not perceiving that they are at risk while on the construction site (see Key Findings 5.7 and 5.8).

- **Impact of nature of work on formworks RT distribution**

Key Finding 6.4: Independent evacuation trials from two high-rise construction sites with formworks at similar levels, involving similar numbers of workers, and in which the workers were engaged in different phases of construction work, produced significantly different response times. Average response times for those involved in high-priority work may be twice as long as for those involved in low-priority work.

The differences in response time are attributed to the nature of the work engaged in at the time of the alarm. Those involved in low-priority work, such as dismantling the formworks following a concrete pour, are likely to exhibit much shorter response times compared to those involved in high-priority work, such as fitting rebar just prior to a concrete pour. Furthermore, as this work did not involve evacuating the formworks during a concrete pour – possibly the work with the highest priority – it is likely that even longer response times could be produced than those reported in this work.

- **Generalised RT distributions for the formworks**

Key Finding 6.5: Two generalised response time distributions (HPFW and LPFW) have been defined to represent the response behaviour of workers in the formworks. The HPFW distribution, based on data from two trials and involving 60 data points, represents the response time distribution for workers involved in high-priority activities such as installing rebar prior to a concrete pour. The LPFW distribution (based on 19 data points) represents the response time distribution for workers involved in low-priority activities such as dismantling the formworks after a concrete pour.

It is recommended that the HPFW is used when dealing with a regulatory required or general safety analysis as it represents the longest response times observed. The LPFW distribution can be used to explore the impact of an evacuation at other times during the construction phase. It is also important to note that the response times may be longer than represented by the HPFW if the evacuation occurs during a work phase of extremely high priority such as a concrete pour.

HPFW response time distribution for the formworks:

$$f(t) = \frac{1}{28.554\sqrt{2\pi}} \exp\left[-\frac{(t - 57.08)^2}{2 * 28.554^2}\right]$$

Where t (response time) is between 0 and 133 s. This can be used for formworks located at up to Level 33 (34 levels).

LPFW response time distribution for the formworks:

$$f(t) = \frac{1}{16.408\sqrt{2\pi}} \exp\left[-\frac{(t - 28.9)^2}{2 * 16.408^2}\right]$$

Where t is between 0 and 51 s. This can be used for formworks located at up to Level 33 (34 levels).

- **Supervisor disengagement time within the formworks**

Key Finding 6.3: The average time for supervisors within the formworks (those engaged in high-priority activities prior to a concrete pour) to disengage from their pre-alarm activities on sounding of the fire alarm is 5.9 s (data from six supervisors). This extremely rapid disengagement is an example of the performance of well-trained and highly motivated staff.

(3) Generalised RT analysis relating to the main building:

The three key findings concerning the generalised response time distributions for the main building were described in Section 4.6.

- **Impact of height on main building RT distribution**

Key Finding 6.6: Three independent evacuation trials from two high-rise construction sites, two with the majority of workers located below Level 10 and one with the majority of workers located between levels 33 and 38, suggest that the response time distribution is not impacted by height.

These results suggest that for high-rise construction sites up to 39 levels, the response times for workers are not impacted by height of construction. This observation may be the result of construction workers not perceiving that they are at risk while on the construction site (see Key Findings 5.7 and 5.8).

- **Generalised RT distribution for the main building**

Key Finding 6.7: A generalised response time distribution has been defined to represent the response behaviour of workers in the main building (MB). The MB distribution, based on data from three trials in two buildings involving 157 data points, represents the response time distribution for workers involved in a variety of activities, such as fitting rebar, glazing and MEP, and includes those working at height and isolated workers within heights of construction up to Level 38 (39 levels).

It is important to note that the MB data-set does not include workers involved in concrete pours or workers in high tower cranes. It is suggested that these workers are likely to contribute to the tail of the response time distribution, possibly extending the tail to longer response times or increasing the frequency of those workers with longer response times.

MB response time distribution for the main building:

$$f(t) = \frac{1}{t0.938\sqrt{2\pi}} \exp\left[-\frac{(\ln t - 3.908)^2}{2 * 0.938^2}\right]$$

Where t is between 0 and 350 s. This can be used for main buildings up to Level 38 (39 levels).

- **Time to disengage and number of tasks undertaken during the response phase for the main building**

Key Finding 6.8: Almost half (41%) of the population react to the alarm in an appropriate manner, rapidly disengaging (in less than 40 s) and starting their evacuation movement phase without undertaking many (at most one task) preparation activities. Nevertheless, almost a third (32%) of the population require more than 60 s to disengage from their pre-alarm activities and, once disengaged, the population as a whole undertake an average of 2.2 tasks, with almost a quarter (23%) of the population undertaking four or more tasks. The long time to disengage and the large number of tasks undertaken explain some of the long response times noted in the trials.

(4) Generalised walking speeds on ladders, temporary stairs and floor surfaces:
The four key findings concerning the generalised walking speeds were described in Sections 4.1, 4.7 and 4.8.

- **Ladder ascent/descent speeds**

Key Finding 1.1: Ascent/descent speeds for workers on ladders have been determined from data derived from 59 workers in Trial 1. Average ladder ascent/descent speeds are considerably slower than the average speed attained on standard building stairs. The average descent speed on ladders (0.45 m/s) is 64% of the descent stair speed (0.7 m/s), while the average ascent speed on ladders (0.42 m/s) is 67% of the ascent stair speed (0.63 m/s). It should be noted that the ladder data has limitations due to the relatively small number of data points collected from the trial, especially for the ladder ascent (two data points).

- **Behaviour on temporary stairs**

Key Finding 7.1: A single flight of a single-lane temporary scaffold dogleg stair, with nine treads per flight, was monitored during two evacuation trials. The most frequently observed spacing between the occupants when three or more occupy the flight was two treads, and the most common number of people that was accommodated on the flight was three for groups consisting of three or more people. The observed spacing is significantly different to that found on regular building stairs which is typically one tread between occupants in high-density situations. The cause of this apparent reluctance of users of temporary stairs to pack more densely is not clear. It may simply be a result of the smaller tread depth found on the temporary stair or it may also be due to the perceived fragility of the stair.

The lower interpersonal spacing on the temporary stair will have a negative impact on the flow capability of the stair, essentially decreasing the flow compared to a permanent stair of similar width. While these observations are based on measuring the behaviour of a large number of people (130) it is possible that the conclusions could be a result of the size of the data-set or the number of people attempting to use the monitored stair at any one time.

- **Walking speeds on temporary stairs**

Key Finding 8.2: The average ascent speed of workers on temporary scaffold dogleg stairs and standard building stairs are very similar while the average descent speed is 84% of the corresponding building stair speed. The device which offers the next fastest performance, in both ascent and descent, is the parallel stair, with the ladder representing the device producing the slowest speeds. The average descent speed on parallel stairs is 74% of the stair descent speed for normal building stairs, and the ascent speed is 79% of the normal stair ascent speed, while for ladders, the average descent and ascent speeds are 52% and 67% of the corresponding normal building stair speeds.

In addition to the impact on speed, the primary difference between the temporary stairs and permanent building stairs is the width of the temporary stairs, which for scaffold stairs is very narrow, only allowing a single person per tread. Thus, overtaking or contraflow is not possible on these stairs. It should be noted that the temporary stair/ladder data has limitations due to the relatively small number of data points available, especially for the ladder ascent (only two data points), and that the speeds on the temporary stairs were determined over just a single flight, so issues such as fatigue are not considered.

- **Generalised walking speed based on surface type**

Key Finding 8.1: A generalised set of walking speed reduction factors has been developed that when combined with the walking speed on concrete can be used to estimate a walking speed when walking across decking, along decking or on decking with rebar. The reduction factors are dependent on the experience of the worker, where inexperienced workers have a greater reduction in walking speed imposed than experienced workers. On average, walking speeds on concrete are greatest followed by, in reducing speed order, across decking, on rebar and along decking.

For inexperienced workers, walking speeds along decking can be as little as 68% of the walking speed on a concrete surface. It is recommended that the inexperienced reduction factors are used when dealing with a regulatory required or general safety analysis as this represents the greatest reduction in walking speeds over each of the surfaces and so is more conservative.

(5) Validation analysis:
The four key findings concerning the validation analysis were described in Section 5.

- **Validation data-set**

Key Finding 9.1: A validation data-set has been defined describing the evacuation of a high-rise construction site. The validation data-set incorporates:

- a building geometry of 33 levels above ground (with the formworks located at Level 33 and the top of the jumpform at Level 34)
- the formworks involving 37 workers
- the main building involving 190 workers
- floor surfaces consisting of concrete, decking and decking with rebar
- temporary scaffold dogleg stairs and ladders
- specified response time distributions for the formworks and main building
- specified starting floor locations for 100 workers
- exit curves for the formworks and main building.

Uncertainties in the data-set include:

- location of obstacles and blockages on the floors excluding the formworks
- incomplete description of starting floor location for 127 workers
- incomplete specification of worker response times.

- **Subjective performance of buildingEXODUS in validation scenario**

Key Finding 9.2: The average exit curve produced by 100 repeat simulations of buildingEXODUS produces a reasonable approximation of the validation data-set. On average, the total evacuation time is over-predicted by 4% while the time for half the population to exit the building is under-predicted by 22%. The average time to clear the jumpform is under-predicted by 15%.

Given the uncertainties in the validation data-set, this is considered an acceptable level of agreement.

- **Objective performance of buildingEXODUS in validation scenario**

Key Finding 9.3: Given the level of uncertainty in the validation data-set, an objective measure of acceptable agreement between model prediction and experimental data has been specified using the performance metric defined using the ERD, EPC and SC. The level of acceptability is based on the performance of the buildingEXODUS software which was subjectively defined as being acceptable. Other software tools used to predict the outcome of the validation scenario producing a similar performance as measured using the metric would be considered to be as good as buildingEXODUS in reproducing the outcome of this trial. The performance measures are:

For the overall predicted exit curve:

(i) ERD ≤ 0.22
(ii) 0.87 ≤ EPC ≤ 1.13
(iii) SC ≥ 0.82 with s/n = 0.07
(iv) Difference between the predicted total evacuation time for the entire building and the measured value to be within 8%.

While for the predicted jumpform exit curve:

(i) ERD ≤ 0.11
(ii) 0.98 ≤ EPC ≤ 1.02
(iii) SC ≥ 0.80 with s/n = 0.05
(iv) Difference between the predicted total exiting time for the jumpform and the measured value to be within 13%.

- **Validation framework for assessing evacuation software suitability for construction site applications**

Key Finding 9.4: A validation framework has been defined to carry out independent validation assessments using the validation data-set presented in this report. All the required information to set up and run the validation scenario within the user's evacuation software has been defined, including the layout of the construction site, the initial population distribution, the end points for evaluation purposes, the population response time distribution, and the arrival times for each worker at each end point. Other parameters to be used in the simulations, such as population gender, age distribution and travel speeds, are also described. A means of objectively assessing the performance of the software in reproducing the validation scenario has also been defined along with levels of acceptable performance based on the relative performance of the software with that of the buildingEXODUS software.

(6) Use of the validated evacuation model to explore improvements in evacuation performance:
The seven key findings concerning suggested improvements in evacuation performance were described in Section 6.

- **Impact on evacuation times of a targeted reduction in worker response times**

Key Finding 10.1: In high-rise construction sites with a population of 525 occupants, decreasing the response time for workers in the main building, resulting in a 27% reduction of the average response time for workers in the main building and reducing their maximum response time by 42%, results in a 26% or 12% decrease in the average total evacuation time for the workers in the main building for construction sites of up to 22 levels and 42 levels respectively (including the formworks). These results suggest that substantial improvements in total evacuation time for the main building can be achieved by reducing the response times of the slowest responders. However, the improvement gains in total evacuation time achieved by reducing the average response time of the main building population diminish with increasing height of construction. It is also noted that the overall evacuation time for the building is not altered as the 125 workers located in the formworks, who are the last to evacuate, are not affected by the reduction in response times.

- **Impact on evacuation times of a global reduction in worker response times**

Key Finding 10.2: For high-rise construction sites of up to 22 levels, halving the response time for all 525 workers results in a 33% decrease in the average total evacuation time for the workers in the main building. However, the overall evacuation time for the building is only decreased by 1%. The modest decrease in overall evacuation time for the entire building is due to the congestion experienced by workers in the formworks attempting to use the sole means of escape: a single ladder.

While achieving a 50% reduction in all the building occupant's response times may be difficult to achieve in practice, it can result in a significant (one-third) reduction in evacuation times for the main building population. However, the time required to clear the formworks and the overall evacuation time for the construction site are constrained by the low flow capacity of the single means of escape from the formworks: a single ladder. It is suggested that the evacuation time for the entire construction site and the formworks could be improved by increasing the flow capacity of the exit route from the formworks. While not explored in this analysis, it is expected that the reduction in total evacuation time for the main building will be less significant with increasing height of construction.

- **Impact on evacuation times for replacing formwork ladders with temporary stairs**

Key Finding 10.3: Replacing the ladders in the formworks with temporary scaffold dogleg stairs reduces the time required to clear the formworks by 17% (67 s) when occupied by 125 agents. While this is a considerable reduction in the time required to clear the formworks, there is considerable congestion at the head of the temporary stair. The time required to clear the formworks could be decreased further if the flow capacity of the exit route from the formworks was increased. This could be achieved through adding another exit route or if the single-lane stair could be replaced with a dual-lane stair. As the last agents to leave the building are from the formworks, the reduction in time required to clear the formworks also decreases the overall building evacuation time. For construction sites of up to 22 levels, the overall building evacuation time is decreased by 8% (51 s), while for construction sites of 42 levels, the overall building evacuation time is decreased by 6% (55 s).

- **Impact on evacuation times of hoists for low construction**

Key Finding 10.4: For relatively low high-rise construction (of up to 22 levels), the use of slow hoists of low capacity (30 people) extends the overall evacuation time by some 37% when compared to the stairs-only case. Increasing the capacity of the slow hoist (40 people) improves the overall performance of the hoist evacuation to the point that it is marginally faster (4%) than the stairs-only case. In contrast, the use of faster hoists with high capacity (40 people) reduces the overall evacuation time by 25% compared with the stairs-only case. However, the evacuation of only the last 50% of the building population is quicker than in the stairs-only case.

It is possible that small delays in engaging the hoists in evacuation activities may improve the overall predicted evacuation performance by increasing the number carried on the first hoist trips.

- **Impact on evacuation times of hoists for high construction**

Key Finding 10.5: As the height of construction is increased (up to 42 levels), the use of slow hoists, regardless of capacity (occupancy of 30 or 40), becomes increasingly inefficient, extending the overall evacuation time by between 27% and 80% depending on capacity, compared with the stairs-only case. However, the use of faster hoists with high capacity (40 occupancy) reduces the overall evacuation time by 31% compared with the stairs-only case. As the height of construction increases, the number of hoist journeys decreases, with each hoist journey carrying more agents.

- **Impact on evacuation times of hoists when 50% of the population use hoists for low construction**

Key Finding 10.6: For relatively low high-rise construction sites (up to 22 levels), if half the population use the stairs during the evacuation, hoists can speed up the evacuation of the construction site relative to the stairs-only case, regardless of the speed and capacity of the hoists. Given the high number of agents using the stairs (50%), the capacity of the hoists is no longer a constraint on hoist performance.

The use of fast hoists with high capacity (40 people) reduces the overall evacuation time by 23% compared to the stairs-only case. This improvement in evacuation performance is only 2% (8 s) slower than the case in which 100% of the agents use the hoists. Furthermore, when only 50% of the agents use the hoists, unlike in the case when 100% use the hoists, the entire population exits the building in a shorter time than if they all used the stairs. As a result, the evacuation is more efficient when 50% of the population use the hoists. Even if the slower hoists are utilised, this results in a 7.6% improvement in evacuation time, regardless of the capacity of the hoists.

- **Impact on evacuation times of hoists when 50% of the population use hoists for high construction**

Key Finding 10.7: In situations where half the population make use of stairs and half the population make use of hoists, the efficiency of using hoists decreases with increasing building height, regardless of the speed or capacity of the hoists. However, the use of fast hoists with high capacity (40 persons) can reduce the total evacuation time by 19% compared to the stairs-only case, while the use of slow hoists with high capacity (40 persons) can reduce the total evacuation time by 3.6%. The use of slow hoists with low capacity (30 persons) can increase the total evacuation time by 16.3%.

The 31 key findings presented in this section together demonstrate an improved understanding of construction worker evacuation behaviour and performance. The collected data characterising the behaviour and performance of construction site workers, coupled with advanced evacuation simulation analysis, demonstrate how evacuation procedures on high-rise construction sites can be optimised to improve evacuation efficiency, making the evacuation process safer. These results satisfy the requirements of project Objective 6.

8 Limitations

As in any study there are limitations imposed on the findings due to practical constraints in collecting data and in performing the various analyses presented in this document. In interpreting the results presented in this work, it is important to take the following constraints into consideration.

8.1 Data collection

1.1 Four full-scale unannounced evacuation trials were conducted involving 926 workers. The four trials involved two different construction sites operated by the same construction contractor and involved sites at essentially two different heights. Ideally, additional evacuation trials would have been conducted, involving different construction contractors and with buildings at different heights of construction. It would also be interesting to explore the impact of 'national culture', both national fire safety culture and national social culture, on construction worker evacuation behaviour and so repeating the experiments in different countries would also be of interest.

1.2 In total, response time data from 270 workers was collected. This did not include all the workers on site during the trials due to limitations in the number of video cameras available. While data from workers involved in a number of different activities typically found on construction sites was collected, not all construction site activities were observed, e.g. those associated with a concrete pour and those involved in operating high cranes. This was primarily due to the need not to seriously disrupt the construction process. Lack of data from these types of activities may result in extremely long response times being excluded from the proposed data-sets.

1.3 Various locations were also not monitored, including workers involved in activities in the basement and workers in staff recreational spaces.

1.4 The trends in response times with increasing building height are limited to the range of building heights encountered during the trials. As a result, they can only be applied with confidence for construction heights of up to 38 levels.

1.5 The data-set associated with worker travel speeds on ladders is limited to monitoring a single ladder. While the number of workers observed descending the ladder is reasonably large (57 data points), only two data points are available for the ascent speed analysis.

1.6 Travel speeds on the temporary stairs were determined over a single flight and so issues such as fatigue are not represented in the data.

1.7 In the walking speed trials workers were observed to be on the verge of running and so the magnitude of the walking speeds achieved are likely to be higher than would normally be expected during an orderly evacuation.

8.2 Questionnaires

2.1 Data from questionnaires represent only 7% of the population that evacuated during the four trials, with all the data being generated from only Trial 1 and Trial 2. However, the data does represent information from 27% of the people who evacuated from these two trials.

2.2 The questionnaire data was collected from construction sites where the height of construction was a maximum of 19 levels and so cannot be applied with confidence for construction heights of above 19 levels.

2.3 The questionnaire data was collected from construction sites operated by a single construction contractor and so the findings may not be generally applicable across the construction industry.

8.3 Validation analysis

3.1 There are a number of uncertainties in the validation data-set including the location of obstacles and blockages on floors, incomplete description of starting location of all workers and incomplete specification of worker response times. These uncertainties must be taken into consideration when assessing the level of software agreement with the validation data-set.

3.2 The validation data-set only includes data from a single evacuation trial and so the natural variation in evacuation behaviour cannot be represented by the validation data-set.
3.3 The validation data-set only represent a single construction site evacuation scenario.

8.4 Suggested improvements to construction site evacuation

4.1 For all the suggested improvements considered, only two benchmark scenarios were considered involving high-rise constructions of two heights (22 and 42 levels maximum height) and a single floor plan, with a single overall total building population (525 occupants), a single formworks population (125) and a single distribution of vertical means of egress. The results obtained for the suggested improvements may be uniquely associated with the benchmark scenarios utilised. In order to assess the robustness of the proposed improvements a range of benchmark scenarios is required.
4.2 When assessing the impact of reduced response times on high-rise construction site evacuation performance only two response time reduction scenarios were investigated – reducing a selection of the extreme response times by 50% and reducing all the response times by 50%. Clearly, other reduction scenarios are possible and should be considered before a definitive conclusion concerning the value in attempting to reduce response times is suggested.
4.3 When assessing the impact of replacing formworks ladders with temporary stairs, this did not take into consideration whether sufficient space was available to introduce the temporary stairs. This may not be an option in all cases.
4.4 When assessing the impact of using hoists to assist in the evacuation, only a single dispatch strategy was considered, with a fixed number of available hoists. In addition, only three different sets of hoist performance characteristics were considered. Clearly all these factors can be varied which will have a significant impact on the conclusions. Furthermore, complex occupant behaviour such as changing one's mind as to whether or not to use the hoist and other factors such as the time at which the hoists are first engaged in evacuation tasks, the amount of time the hoist waits on a floor before leaving, and whether or not the hoist requires an operator, will all impact the efficiency of using the hoist for evacuation.
4.5 When assessing the impact of using the hoists to assist in evacuation, the potential impact of fire and smoke was not taken into consideration.

9 Concluding comments

The project has developed a unique evidence base characterising, for the first time, the actual performance and behaviour of construction workers during emergency evacuation. It consists of (i) response times for workers in the main building and the formworks, as measured from the sounding of the alarm in the main building, (ii) worker walking speeds on different types of surfaces, such as concrete, decking and decking with rebar, and (iii) worker ascent and descent speeds on temporary dogleg and parallel scaffold stairs and ladders. The data has been incorporated in the building evacuation simulation tool buildingEXODUS, providing it with a unique capability to simulate evacuation from high-rise construction sites. The performance of the software has been validated using measured data collected from the trials. The validated software has been used to explore how evacuation procedures for high-rise construction sites can be improved, including the impact of reducing worker response times, replacing ladders with temporary scaffold stairs within the formworks and using hoists to assist in evacuation.

IMPACT OF PROJECT FINDINGS

The use of the evidence base and the modelling software will inform the development of more reliable evacuation procedures, improving the work environment through better preparation for, and management of, on-site emergency evacuation, and advancing the safety of construction workers. Potential uses of the evidence base and modelling approach include:

- addressing the identified limitations, assumptions and omissions in guidelines and regulations, including those produced by the HSE, through the incorporation of the evidence base
- use of the evidence base by construction site health and safety managers to inform training of workers and the formulation of best practice
- use of suitably validated modelling tools by construction site managers to define enhanced evacuation procedures.

This impact will be aided through the wide-scale dissemination of the work through:

- papers in peer-reviewed journals
- presentations at national and international conferences
- publication in professional journals
- social media outlets.

FUTURE RESEARCH

Further research is required to extend the evidence base, ensuring that the findings are robust. This includes:

- undertaking additional unannounced evacuation trials of high-rise buildings of similar heights to those studied here to ensure that the results are truly generalisable
- undertaking additional unannounced evacuation trials of high-rise buildings of greater heights to those studied here to determine if there are any limitations on the applicability of the trends identified
- undertaking additional unannounced evacuation trials of high-rise buildings to collect data associated with work not observed in these trials, e.g. concrete pours
- undertaking additional unannounced evacuation trials in different countries to explore the impact of ‘national culture’, both national fire safety culture and national social culture, on construction worker evacuation behaviour
- undertaking additional unannounced evacuation trials to establish more robust validation data-sets
- undertaking additional experiments to collect additional data for ladders, temporary stairs and floor surfaces.

The validated model could be used to undertake a wider, more systematic study into various approaches to improve evacuation efficiency from high-rise construction sites. This could, for example, include:

- additional benchmark scenarios to determine the robustness of proposed improvement strategies
- a wider study of hoist scenarios to identify optimal evacuation strategies
- a wider study of exiting from the formworks
- the impact of fire/smoke on the evacuation of workers.

Finally, various means of improving worker response to alarms and their wayfinding ability should be explored. This could include:

- developing an enhanced training programme emphasising the importance of rapid response to alarms
- developing technology to enhance worker response to alarms, e.g. use of pagers, mobile phones or other novel devices such as a Wi-Fi-enabled vibrator built into helmets
- developing active RFID tracking technology to identify the location of each worker on site
- developing portable dynamic signage systems that could be deployed on construction sites to improve the affordance of emergency signage.

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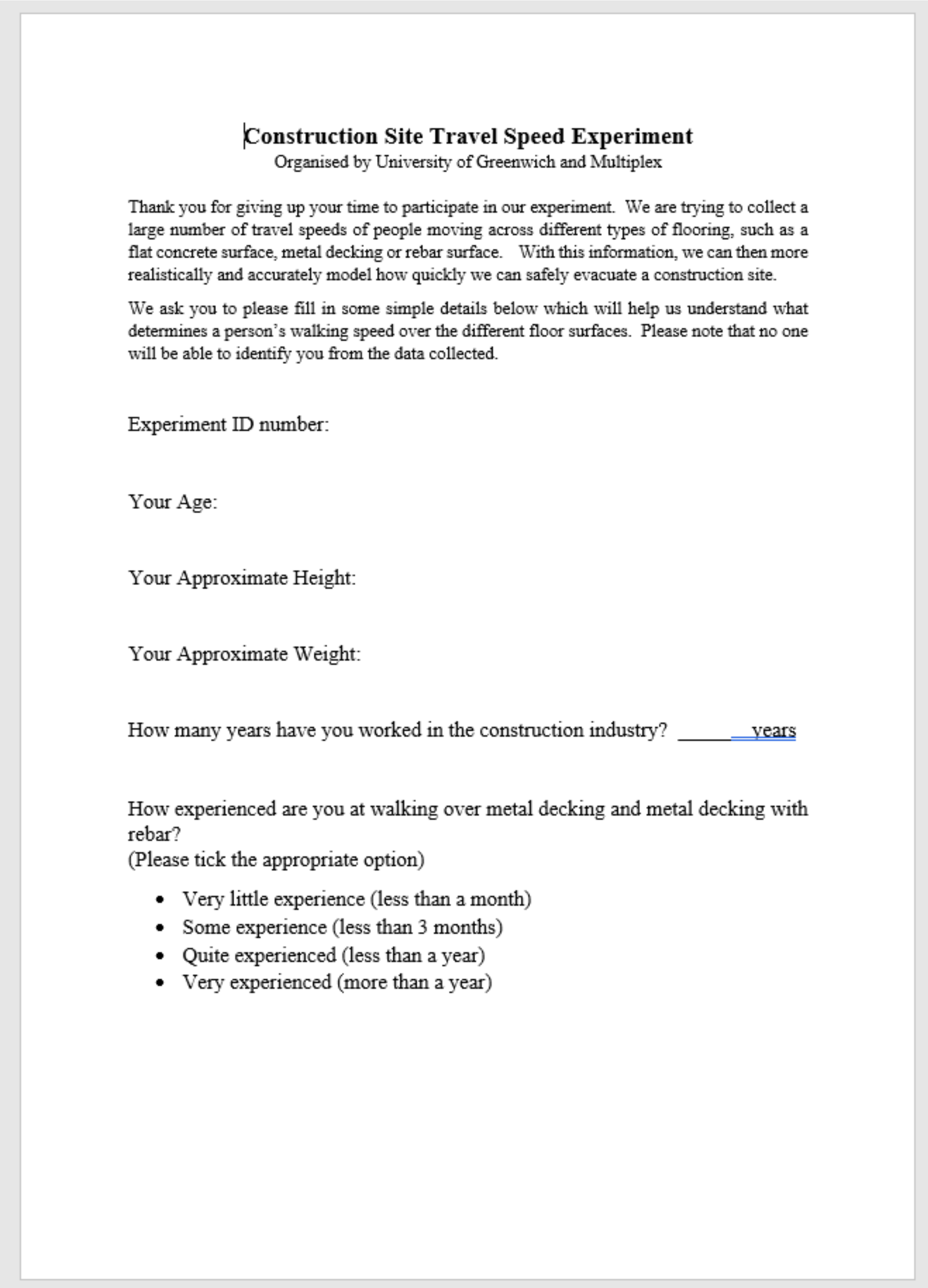
Appendix 1 – Participant data and consent form for the walking speed trials



Construction Site Travel Speed Experiment

Organised by University of Greenwich and Multiplex

Thank you for giving up your time to participate in our experiment. We are trying to collect a large number of travel speeds of people moving across different types of flooring, such as a flat concrete surface, metal decking or rebar surface. With this information, we can then more realistically and accurately model how quickly we can safely evacuate a construction site.

We ask you to please fill in some simple details below which will help us understand what determines a person's walking speed over the different floor surfaces. Please note that no one will be able to identify you from the data collected.

Experiment ID number:

Your Age:

Your Approximate Height:

Your Approximate Weight:

How many years have you worked in the construction industry? __________ years

How experienced are you at walking over metal decking and metal decking with rebar?
(Please tick the appropriate option)

- Very little experience (less than a month)
- Some experience (less than 3 months)
- Quite experienced (less than a year)
- Very experienced (more than a year)

Appendix 2 – Questionnaires distributed to workers following the evacuation trials

BACKGROUND – select only one answer per question.

Q1. What is your age?

☐ 18-24 ☐ 25-34 ☐ 35-44 ☐ 45-54 ☐ 55-64 ☐ 65-74

Q2a. Is English your first language?

☐ Yes ☐ No

Q2b. How well can you speak English?

☐ Not at all ☐ Not well ☐ Well ☐ Very well

Q2c. How well can you read English?

☐ Not at all ☐ Not well ☐ Well ☐ Very well

Q3. Which site are you working on?

☐ 100 Bishopsgate, London
☐ 98 Fetter Lane, London
☐ LSQLONDON, London
☐ 22 Bishopsgate, London
☐ London Wall Place, London
☐ Verde SW1, London

Q4. How long have you been working on this site?

☐ Less than 1 week
☐ Less than 3 months
☐ Other: ……………………………………
☐ Less than 1 month
☐ Less than 6 months

Q5. How do you normally travel up and down on this site?

☐ I always use stairs
☐ I always use the hoist
☐ I use stairs sometimes and use the hoist at other times
☐ Other: ……………………………………

Q6. When you hear the alarm to evacuate the site, what are you supposed to do?

☐ Continue working until someone tells me what to do
☐ Copy what other workers are doing
☐ Ask another worker what to do
☐ Evacuate immediately, following the fire marshal or supervisor's directions (if possible)
☐ Make my workplace safe, then evacuate
☐ I do not know
☐ Other: ……………………………………

THANK YOU. NOW...

3

The following questions will ask about your evacuation experience, from the start of the evacuation (when an alarm began to sound) to the end (when you had evacuated to street level). **Select only one answer per question, unless instructed otherwise.**

THE EVACUATION – YOUR LOCATION

Q7. Where were you located when you realised that you had to evacuate?

☐ Jumpform ☐ Core ☐ Floor ☐ Basement ☐ Other: ……………………………

Q8. What level were you working on when you realised that you had to evacuate?

Level number __

THE EVACUATION – THE ALARM AND EVACUATION DECISION

Q9. Describe what made you aware that something was happening. You may select more than one answer.

☐ The alarm
☐ I saw other workers react (e.g. they stopped working, started leaving)
☐ Someone told me personally to evacuate
☐ I saw or heard fire engines arriving
☐ Other: ……………………………………

Q10. Why could you not hear the alarm? You may select more than one answer.

☐ Not applicable – I heard the alarm
☐ I was wearing hearing protection (e.g. earplugs, earmuffs)
☐ I or other workers nearby were involved in noisy tasks
☐ I was not near an alarm
☐ I do not know
☐ Other: ……………………………………

Q11. When you became aware something was happening, did you believe there was a real emergency occurring?

☐ Yes ☐ No

Q12. Describe the FIRST action you took when you became aware something was happening.

☐ I ignored what was happening and continued with my task
☐ I completed my task
☐ I tried to get more information
☐ I alerted other workers
☐ I shutdown or secured machinery
☐ I started to evacuate
☐ Other: ……………………………………

4

Q13. What task had you been doing when you became aware something was happening?

- ☐ Tying steel rebar
- ☐ Finishing concrete
- ☐ Installing steel frame
- ☐ Installing lifts
- ☐ Laying bricks or blocks
- ☐ Installing shutters
- ☐ Installing decking
- ☐ Stud welding
- ☐ Installing cladding
- ☐ Other: ....
- ☐ Pouring concrete
- ☐ Installing decking rebar
- ☐ Mechanical and/or electrical installation
- ☐ Installing dry lining

Q14. Was it important TO YOU that you completed this task before evacuating?

☐ Not at all important ☐ A little important ☐ Important ☐ Very important

Q15. Was it important TO YOUR EMPLOYER that you completed this task before evacuating?

☐ Not at all important ☐ A little important ☐ Important ☐ Very important

Q16. What made you start to evacuate?

- ☐ The alarm
- ☐ I had finished what I was doing and so I could go
- ☐ Everyone else was leaving or had now left
- ☐ An authority figure told me to leave
- ☐ Another worker told me to leave
- ☐ I saw or heard fire engines arriving
- ☐ Other: ....

THE EVACUATION – EXIT ROUTE

Q17. How did you find an exit route?

- ☐ I remembered the evacuation diagram
- ☐ I took the same route out as I use to come in
- ☐ I followed other workers to an exit
- ☐ An authority figure told me which exit route to use
- ☐ Another worker told me which exit route to use
- ☐ I looked for an emergency exit sign
- ☐ Other: ....

Q18a. Did your exit route go directly to the ground level?

- ☐ Yes
- ☐ No. I had to go up first before I could go down.
- ☐ Other: ....

Q18b. If you selected "No" to Q18a, were you surprised by having to go up before going down?

☐ Not at all ☐ A little surprised ☐ Moderately surprised ☐ Very surprised
☐ Not applicable

5

Q18c. If you selected "No" to Q18a, how did you know you had to first go up before going down?

- ☐ Not applicable
- ☐ I remembered the evacuation diagram
- ☐ I have used this route before
- ☐ I followed other workers
- ☐ An authority figure told me where to go
- ☐ Another worker told me where to go
- ☐ I looked for an emergency exit sign
- ☐ Other: ....

AND FINALLY… RISK PERCEPTION

Q19. Did you sense you were in danger during the evacuation? Select one answer for each row.

	Not at all	A little danger	Some danger	Extreme danger
When you became aware something was happening	☐	☐	☐	☐
When you started to evacuate	☐	☐	☐	☐
When you saw or heard fire engines arriving	☐	☐	☐	☐

Q20. Do you sense you are in danger when working on a construction site under everyday (i.e. non-emergency evacuation) conditions? Select one answer for each row.

	Not at all	A little danger	Some danger	Extreme danger
This particular site	☐	☐	☐	☐
Construction sites in general	☐	☐	☐	☐

Q21. How likely is it you would engage in the following activities or behaviours if you were in those situations? Select one answer for each row using the 7-point scale below.

1	2	3	4	5	6	7
Extremely Unlikely	Moderately Unlikely	Somewhat Unlikely	Not Sure	Somewhat Likely	Moderately Likely	Extremely Likely

	Rating (1-7)
Getting in a car with a driver who you know to have had two alcoholic drinks at a bar.	
Exceeding the speed limit on a motorway (freeway).	
Disagreeing with an authority figure on a major issue.	
Driving a car without wearing a seat belt.	
Taking a skydiving class.	
Riding a bicycle without a helmet.	
Crossing the road when the "don't walk" sign is indicated.	
Betting a day's income on the outcome of a sporting event.	
Walking home alone at night in an unsafe area of town.	

THIS IS THE END OF THE QUESTIONNAIRE.
THANK YOU FOR YOUR TIME.

6

Appendix 3 – Ethics approval letter

UNIVERSITY
of
GREENWICH

Dr Lynn Hulse
University of Greenwich
Faculty of Architecture, Computing & Humanities
Department of Mathematical Sciences
QM264, Queen Mary Ct.
Greenwich Campus

Direct Line 020 8331 8842
Direct Fax 020 8331 8824
Email researchethics@gre.ac.uk
Our Ref UREC/16.1.5.7
Date: 28th October 2016

Dear Lynn,

University Research Ethics Committee – Minute 16.1.5.7

TITLE OF RESEARCH: Construction Site Evacuations

I am writing to confirm that the above application has been **approved** by Chair's Action on behalf of the Committee and that you have permission to proceed.

I am advised by the Committee to remind you of the following points:

- You must notify the Committee immediately of any information received by you, or of which you become aware, which would cast doubt upon, or alter, any information contained in the original application, or a later amendment, submitted to the Committee and/or which would raise questions about the safety and/or continued conduct of the research;
- You must comply with the Data Protection Act 1998;
- You must refer proposed amendments to the protocol to the Committee for further review and obtain the Committee's approval thereto prior to implementation (except only in cases of emergency when the welfare of the subject is paramount).
- You are authorised to present this University of Greenwich Research Ethics Committee letter of approval to outside bodies in support of any application for further research clearance.

On behalf of the Committee may I wish you success in your project.

Yours sincerely

John Wallace
Secretary, University Research Ethics Committee

University of Greenwich
Greenwich Campus
Old Royal Naval College
Park Row

Appendix 4 – Interpersonal spacing on stair flight for Trial 2 and Trial 4

The interpersonal spacing, group size and number of workers occupying the stairs at any one time were derived from a single flight of temporary scaffold dogleg stairs in Trial 2 and Trial 4. The data extracted from the video upon which the analysis in Section 4.7 is based is presented in Table 65 and Table 66.

Table 65. Interpersonal spacing on stair flight derived from Trial 2.

Time stamp (hh:mm:ss:ff*)	**Event**	**Group #**	**Group size**	**Sampling duration (s)**	**Worker(s) on stairs**	**Average spacing (tread)**	**Frequency of spacing on stair flight**					
							1	**2**	**3**	**4**	**5**	**6**
09:00:35:12	Group Start	1	2	3.12	1							
09:00:37:03					2	2.0		1				
09:00:38:15					2	3.0			1			
09:03:25:10	Group Start	2	4	7.08	1							
09:03:27:03					2	3.0			1			
09:03:28:10					2	3.0			1			
09:03:29:16					2	4.0				1		
09:03:29:16					2	4.0				1		
09:03:31:06					2	3.0			1			
09:03:32:12					2	3.0			1			
09:03:35:09	Group Start	3	3	4.76	1							
09:03:36:14					2	2.0		1				
09:03:37:24					3	3.0		1		1		
09:03:40:03					2	2.0		1				
09:03:47:04	Group Start	4	3	4.2	1							
09:03:48:19					2	4.0				1		
09:03:49:19					2	4.0				1		
09:03:50:01					2	3.0			1			
09:03:51:09					2	3.0			1			
09:03:55:21	Group Start	5	2	2.08	1							
09:03:56:24					2	3.0			1			
09:03:57:23					2	3.0			1			
09:03:59:00	Group Start	6	2	2.16	1							
09:04:00:10					2	4.0				1		
09:04:01:04					2	3.0			1			
09:04:09:22	Group Start	7	4	5.24	1							
09:04:10:23					2	2.0		1				
09:04:12:07					3	3.0		1		1		
09:04:13:09					3	3.0		1		1		
09:04:15:03					2	2.0		1				
09:04:32:01	Group Start	8	2	2.56	1							
09:04:33:08					2	3.0			1			
09:04:34:15					2	3.0			1			
09:04:45:11	Group Start	9	2	2.68	1							
09:04:46:18					2	2.0		1				
09:04:48:03					2	3.0			1			
09:09:15:24	Group Start	10	2	4.24	1							
09:09:17:17					2	2.0		1				
09:09:20:05					2	3.0			1			

*This is the number of video frames. Each video frame is equal to 1/25 of a second.

Table 66. Interpersonal spacing on stair flight derived from Trial 4.

Time stamp (hh:mm:ss:ff)	**Event**	**Group #**	**Group size**	**Sampling duration (s)**	**Worker(s) on stairs**	**Average spacing (tread)**	**Frequency of spacing on stair flight**					
							1	**2**	**3**	**4**	**5**	**6**
09:31:56:19	Group Start	1	2	3.16	1							
09:31:58:10					2	2.0		1				
09:31:59:23					2	3.0			1			
09:32:07:06	Group Start	2	2	2.76	1							
09:32:08:16					2	3.0			1			
09:32:10:00					2	2.0		1				
09:32:16:12	Group Start	3	2	3.04	1							
09:32:18:00					2	2.0		1				
09:32:19:13					2	4.0				1		

09:32:24:14	Group Start	4	2	3..24	1							
09:32:26:20					2	4.0				1		
09:32:27:20					2	5.0					1	
09:32:50:14	Group Start	5	2	3.12	1							
09:32:52:03					2	3.0			1			
09:32:53:17					2	3.0			1			
09:32:59:16	Group Start	6	2	3..08	1							
09:33:01:10					2	3.0			1			
09:33:02:18					2	2.0		1				
09:34:01:10	Group Start	7	2	2.04	1							
09:34:02:18					2	3.0			1			
09:34:03:11					2	5.0					1	
09:34:26:09	Group Start	8	4	7.32	1							
09:34:28:08					2	2.0		1				
09:34:30:00					3	2.0		2				
09:34:31:05					3	2.0		2				
09:34:31:13					3	2.0		2				
09:34:32:09					3	2.0		2				
09:34:33:17					2	2.0		1				
09:34:51:15	Group Start	9	2	2.64	1							
09:34:52:19					2	2.0		1				
09:34:54:06					2	2.0		1				
09:35:12:22	Group Start	10	2	2.12	1							
09:35:14:02					2	3.0			1			
09:35:15:00					2	3.0			1			
09:35:19:18	Group Start	11	8	11.24	1							
09:35:21:01					2	1.0	1					
09:35:22:06					3	1.5	1	1				
09:35:23:09					3	2.0		2				
09:35:23:17					3	2.0		2				
09:35:24:10					3	2.5		1	1			
09:35:25:03					3	3.0	1				1	
09:35:26:08					3	2.0	1		1			
09:35:26:23					3	2.5	1			1		
09:35:28:06					3	3.0			2			
09:35:29:06					2	5.0					1	
09:35:29:14					2	2.0		1				
09:35:30:24					2	2.0		1				
09:35:49:19	Group Start	12	2	2.88	1							
09:35:51:09					2	4.0				1		
09:35:52:16					2	3.0			1			
09:35:55:09	Group Start	13	4	5.56	1							
09:35:56:15					2	2.0		1				
09:35:58:07					3	3.0		1		1		
09:35:59:01					2	5.0					1	
09:35:59:19					2	3.0			1			
09:36:00:23					2	3.0			1			
09:36:41:11	Group Start	14	7	10.96	1							
09:36:43:04					2	2.0		1				
09:36:44:07					3	2.0		2				
09:36:45:05					3	2.0		2				
09:36:45:17					3	2.0		2				
09:36:46:13					3	2.0		2				
09:36:46:23					3	2.0		2				
09:36:47:12					3	2.5		1	1			
09:36:48:23					3	2.5		1	1			
09:36:49:09					3	2.5		1	1			
09:36:50:12					3	3.0		1		1		
09:36:52:10					2	2.0		1				
09:36:53:22	Group Start	15	3	4.28	1							
09:36:55:01					2	2.0		1				
09:36:56:04					3	2.0		2				
09:36:57:03					3	1.0	2					
09:36:58:04					2	2.0		1				
09:37:06:11	Group Start	16	8	11.84	1							
09:37:08:09					2	3.0			1			
09:37:10:00					3	3.0		1		1		

09:37:11:13					3	2.0		2				
09:37:12:06					3	2.0	1		1			
09:37:12:15					3	1.5	1	1				
09:37:13:17					3	2.0	1		1			
09:37:14:03					3	1.5	1	1				
09:37:14:21					3	2.0	1		1			
09:37:15:08					3	2.0		2				
09:37:16:10					3	2.0		2				
09:37:17:05					3	3.0			2			
09:37:18:07					2	5.0					1	
09:37:20:15	Group Start	17	2	2.04	1							
09:37:20:24					2	2.0		1				
09:37:22:16					2	2.0		1				
09:37:33:06	Group Start	18	4	5.28	1							
09:37:34:07					2	2.0		1				
09:37:35:18					3	2.5		1	1			
09:37:36:03					3	2.5		1	1			
09:37:37:06					3	3.0			2			
09:37:38:13					2	3.0			1			
09:38:01:24	Group Start	19	2	2.8	1							
09:38:03:06					2	2.0		1				
09:38:04:19					2	3.0			1			
09:38:10:23	Group Start	20	2	2.4	1							
09:38:12:06					2	3.0			1			
09:38:13:08					2	4.0				1		
09:38:23:03	Group Start	21	7	10.76	1							
09:38:24:16					2	2.0		1				
09:38:26:20					3	2.5		1	1			
09:38:27:02					3	3.0		1		1		
09:38:28:01					3	2.5	1			1		
09:38:28:12					3	2.5	1			1		
09:38:29:10					3	1.5	1	1				
09:38:30:11					3	2.0	1		1			
09:38:30:21					3	2.5		1	1			
09:38:32:06					3	2.5		1	1			
09:38:32:19					3	2.5		1	1			
09:38:33:22					2	4.0				1		
09:38:36:01	Group Start	22	4	4.92	1							
09:38:37:06					2	2.0		1				
09:38:38:12					3	2.5		1	1			
09:38:38:24					3	2.5		1	1			
09:38:39:24					3	2.5		1	1			
09:38:40:24					2	3.0			1			
09:39:21:17	Group Start	23	2	2.52	1							
09:39:23:00					2	3.0			1			
09:39:24:05					2	4.0				1		
09:39:34:12	Group Start	24	3	5.76	1							
09:39:36:21					2	4.0				1		
09:39:38:00					2	6.0						1
09:39:38:13					2	1.0	1					
09:39:40:06					2	3.0			1			
09:39:55:05	Group Start	25	7	10.04	1							
09:39:56:20					2	2.0		1				
09:39:58:02					3	1.5	1	1				
09:39:59:10					4	1.7	1	2				
09:40:00:10					3	2.0	1		1			
09:40:00:21					3	1.5	1	1				
09:40:02:05					4	1.7	1	2				
09:40:02:20					3	2.0		2				
09:40:03:13					3	2.5		1	1			
09:40:03:23					3	2.5		1	1			
09:40:05:06					2	2.0		1				
09:40:50:13	Group Start	26	2	2.76	1							
09:40:51:16					2	1.0	1					
09:40:53:07					2	3.0			1			
09:41:00:17	Group Start	27	2	3.52	1							
09:41:02:03					2	2.0		1				

09:41:04:05					2	3.0			1			
09:41:19:15	Group Start	28	2	2.24	1							
09:41:20:17					2	2.0		1				
09:41:21:21					2	4.0				1		
09:42:08:19	Group Start	29	4	6.48	1							
09:42:10:02					2	2.0		1				
09:42:11:15					2	4.0				1		
09:42:12:12					2	4.0				1		
09:42:13:18					3	3.0		1		1		
09:42:15:06					2	4.0				1		
09:42:38:01	Group Start	30	3	4.24	1							
09:42:39:11					2	3.0			1			
09:42:40:13					2	4.0				1		
09:42:41:01					2	3.0			1			
09:42:42:07					2	3.0			1			
09:47:38:11	Group Start	31	2	4.92	1							
09:47:40:19					2	2.0		1				
09:47:43:09					2	3.0			1			
09:48:53:18	Group Start	32	2	3	1							
09:48:55:02					2	2.0		1				
09:48:56:18					2	2.0		1				

Appendix 5 – Data dictionary for video analysis of response phase behaviours

Presented in Table 67 are the various codes, along with their meanings, used to categorise the workers and their actions just prior to and during the evacuation. Markers were inserted into the video timeline, using Adobe Premiere Pro, which identify the time when a specific worker is seen moving into the next stage of their response phase: from the start of the alarm (marker called 'AAT'), to the start of their activity stage (marker called 'SAT'), to the end of their response phase (marker called 'ERP'). If a worker is seen to have received a supervisor intervention then a 'SIT' marker was inserted into the timeline to identify when the worker received the intervention.

Other information relating to the worker such as gender, approximate age and group status was noted in the AAT marker. The nature of the action/information tasks undertaken during the activity stage by the worker was noted in the ERP marker.

Table 67. Response phase data dictionary.

#	Marker name		Value	Meaning
1	**AAT**		Time (auto-extracted)	Alarm Activation Time
	Parameters:	Px	Number: 1 to Max number of workers in scene	Incremental value indicating examined worker in video file
		Gender	M, F or U	Male, Female or Unidentifiable
		Age group ID	Number: 0, 1, 2, 3	Approximate age group 0. Unidentifiable 1. Adolescent (16–19) 2. Young person (20–39) 3. Older person (40+)
		Level of seniority on site	Number: 1, 2, 3, 4	1. Orange helmet – crane supervisor 2. Black helmet – supervisor 3. White helmet – experienced worker 4. Blue helmet – inexperienced person
		Pre-alarm activity ID	Number: 0 to 14	Pre-alarm stage activities 0. Unidentifiable (e.g. not in camera view at AAT) 1. Standing 2. Walking 3. Fixing steelwork / rebar 4. installing decking 5. installing rebar 6. Installing MEP 7. Finishing concrete 8. Installing glazing 9. Supervising (groups of workers) 10. Supervising (crane operators) 11. On raised platform (ladder or cherry picker) 12. Cleaning 13. Operating machinery (including cherry pickers)

		Group status	Number: 0 to 3	Group status when alarm was sounded 0. Unidentifiable 1. worker is alone 2. worker appears to be alone but within the vicinity of other workers 3. worker is operating within a team of workers
		Floor surface type	Number: 1 to 6	1. Core 2. Jump / Slip form 3. Concrete flooring 4. Rebar flooring 5. Metal decking 6. Ground floor
		If pre-alarm activity is 0 – what activity appears to be performed by the worker		Assumed pre-alarm stage activities 0. Unidentifiable – No Idea 1. Standing 2. Walking 3. Fixing steelwork / rebar 4. installing decking 5. installing rebar 6. Installing MEP 7. Finishing concrete 8. Installing glazing 9. Supervising (groups of workers) 10. Supervising (crane operators) 11. On raised platform (ladder or cherry picker) 12. Cleaning 13. Operating machinery (including cherry pickers)
2	**SCS**		Time (auto-extracted)	Start of Cognition Stage
3	**SAS**		Time (auto-extracted)	Start Activity Stage
4	**SIT**		Time (auto-extracted)	Supervisor Intervention Time
6	**ERP**		Time (auto-extracted)	End Response Phase
	Parameters:	Num of ATBs	Number: 1 to 10	Number of observed ATs
		Num of ITBs	Number: 1 to 10	Number of observed ITs
		Num of ATAs	Number: 1 to 10	Number of observed ATs after worker intervention
		Num of ITAs	Number: 1 to 10	Number of observed ITs after worker intervention
		List of AT IDs	Num-of-ATs numbers ranging from 1 to 16 (or more)	Action task type 1. Remove tool belt 2. Put down/secure tools/equipment 3. Put down/secure materials 4. Continue work 5. Collect tools or clothing 6. Wait for others (for example need unhooking or a supervisor waiting for staff to respond) 7. Adjust clothing (hard hat / ear muffs / hi viz etc.) 8. Operate machinery (e.g. cherry picker) 9. Move to another location (possibly collecting something)

<table>
<tr><td></td><td></td><td></td><td></td><td>10. Secure area
11. Check area
12. Climb down ladder/platform
13. Unhook harness
14. Other....</td></tr>
<tr><td></td><td></td><td>List of IT IDs</td><td>Num-of-ITs numbers ranging from 1 to 7 (or more)</td><td>Information task type
20. Use mobile phone
21. Shout instructions
22. Talk to others
23. Receive instruction from supervisor
24. Move to another location to seek information
25. Look around for information
26. Other...?</td></tr>
<tr><td></td><td></td><td colspan="3">NOTE – The order is important and should follow:

#ATB,#ITB,#ATA,#ITA,ATB_{ID1},...,ATB_{ID10},ITB_{ID1},...,ITB_{ID10},ATA_{ID1},..., ATA_{ID10}, ITA_{ID1},..., ITA_{ID10}

Also, BEFORE and AFTER refer to the first crew intervention.</td></tr>
<tr><td>7</td><td colspan="3">OBS (1 frame after ERP)</td><td>Any relevant observations</td></tr>
</table>

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