

Construction site evacuation safety: Evacuation strategies for tall construction sites



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In this document, you'll find a summary of the independent study we commissioned from the University of Greenwich, *Construction site evacuation safety: Evacuation strategies for tall construction sites*.



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Construction site evacuation safety

Evacuation strategies for tall construction sites

What's the problem?

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 need for large-scale evacuation. In London alone, an estimated 541 high-rise building projects were planned as of the end of 2018. While fire is not a major cause of death or injury on UK construction sites, given the high frequency of fires and the number of workers involved, 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. It is therefore essential that large-scale construction sites have robust plans for safe and timely emergency evacuation.

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.

We commissioned Professor Ed Galea and his team from the Fire Safety Engineering Group of the University of Greenwich to investigate high-rise construction site evacuation. There were six key objectives:

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

What did our researchers do?

To address the core objectives, the team split the study 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 Multiplex sites in London were selected (22 Bishopsgate (22 BG) and 100 Bishopsgate (100 BG)), with each site evacuated on two occasions while at different heights of construction (see Table 1). The second type of trial consisted of five experiments to collect walking speed data. These trials involved workers walking over four different floor surfaces: concrete, decking (both across and along the ridges) and decking with rebar.

Workers also ascended and descended temporary scaffold stairs arranged in dog-leg and parallel configurations. These trials were conducted at the same location as the evacuation trials.

The data from both types of trial were collected through the use of video cameras and participant questionnaires. Once the trials and data handling were planned, ethical approval to conduct the trials was obtained. Only once ethical approval was obtained could the trials begin. This task contributed to objectives 1 to 4.

Task 2 – Data collection

Each site was prepared for the trials which involved setting up the video recording equipment. For the evacuation trials this had to be done the night before the trials were conducted so as not to alert the workers. In total some 926 workers took part in the four unannounced

full-building evacuation trials (see Table 1). In total 152 workers participated in the five walking speed trials, generating a total of 671 data points. These include more than 100 walking speed data points for each floor surface type, 73 ascent/descent data points for the temporary scaffold dog-leg stair configuration and 53 data points for the parallel stair configuration. In addition, some 59 ladder ascent/descent speeds were collected. This task contributed to objectives 1 to 4.

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. The extracted data were then analysed to understand better how workers perceive risk, 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 contributed to objectives 1 to 3.

Task 4 – Validation analysis

The human performance data collected in Task 3 were used to calibrate the buildingEXODUS evacuation modelling software. To be able to make reliable predictions of human behaviour during evacuation, this software requires reliable human performance data describing parameters such as response times, travel speeds and wayfinding choices. Other software calibration was 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 was then used to assess the performance of the calibrated buildingEXODUS evacuation model in performing evacuation simulations of construction sites by comparing its predictions with the behaviour observed in one of the full-scale unannounced evacuation trials. This task contributed to 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 were systematically examined and changes in evacuation performance were quantified. The potential enhancements investigated involved improving the response time of workers, replacing ladders with temporary stairs in the formworks and use of hoists for evacuation. This task contributed to objective 5.

Taken collectively, the completion of Tasks 1 to 5 addresses the requirements of objective 6.

What did our researchers find out?

Table 1 presents a high-level summary of the overall results from the four full-scale unannounced evacuation trials. The results show that the average response times for workers in the formworks varied from 29 to 58 seconds while the average response time for workers in the main building varied from 62 to 76 seconds. Total evacuation times for the high-rise buildings varied from 9' 14" to 20' 47", depending on height of construction and number of workers, with exit flows varying from 0.08 to 0.32 people per second. 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 only a few workers exiting early (those located low down in the main part of the building) while the majority exited much later. Excluding the data from this trial, exit flows measured (in trials where the workers distributed throughout the buildings) varied from 0.25 to 0.32 people per second, with a weighted mean exit flow of 0.29 people per second.

Table 1. 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 (12m 46s)	0.25
Trial 2 28/02/17	22 BG	43*	13*	56	-	554 (9m 14s)	0.08
Trial 3 04/10/17	100BG	308	38		62	1098 (18m 18s)	0.29
Trial 4 16/11/17	22BG	388	32*	58*	75	1247 (20m 47s)	0.32

*Excludes three workers from the South Core; XNorth Core; +excludes six supervisors.

The analysis of the collected experimental data and evacuation simulation results produced 31 key findings which are now summarised.

1. Worker risk perception and behaviour assessed through questionnaire analysis

The questionnaires provided insight into workers' knowledge of evacuation procedures and their perceptions of and response to the evacuation 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 provided statistically meaningful results, at least for these two trials.

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 a supervisor 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 about 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 the sites is a credit to the safety culture developed by the contractor, 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 and not wasting time collecting belongings prior to evacuating.

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. Worker response to evacuation alarms assessed through video analysis of unannounced evacuation trials

Occupant response time (RT) is a key evacuation parameter as it is a measure of how long a person takes between hearing the evacuation alarm and beginning purposeful movement towards an exit or place of safety. RT is dependent on a number of factors including the type of building, the demographic characteristics of the occupants, the activities that they are involved in at the time of the alarm and the type of alarm. Typically, the RT for building occupants is represented by a log-normal probability distribution, with the majority of people reacting quite quickly, while some people take longer to respond. Prior to this study, RT for workers involved in high-rise construction had not been measured. As a result, most construction site evacuation guidelines simply assume workers react almost immediately on hearing the alarm, downing tools and starting their evacuation. This project, for the first time, has quantified the response behaviour of construction workers and in the process has uncovered a number of important and unexpected results.

An important finding of this research 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 four 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 six minutes while the longest RTs in the formworks were around two 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 RT distributions for workers in the formworks and the main building do not appear to be affected by the height of construction, at least for formworks located at up to 33 levels high, and main buildings up to 38 levels high. As a result it is possible to define generalised RT distributions for use in high-rise construction sites, at least up to 38 levels high.

Furthermore, the nature of the work and the phase of construction appear to influence the RTs of workers within the formworks. The average RTs for those involved in high-priority work (such as fitting rebar just prior to a concrete pour) were approximately twice as long as that for those involved in low-priority work (such as dismantling the formworks following a concrete pour).

It was noted that in the main building almost half (41%) of the population react to the alarm in an appropriate manner, rapidly disengaging (in less than 40 seconds) 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 seconds to disengage from their pre-alarm activities. Once disengaged, the population as a whole undertakes an average of 2.2 tasks; however, almost a quarter (23%) undertake four or more tasks. The long time to disengage and the large number of tasks undertaken once disengaged explain some of the long RTs 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 seconds. This extremely rapid disengagement is an example of the performance of well-trained and highly motivated staff.

Three generalised RT distributions have been defined to describe how workers on high-rise construction sites behave: two represent the response behaviour of workers in the formworks (HPFW (High-Priority Formworks) and LPFW (Low-Priority Formworks)), and one represents the response behaviours of workers in the main building (MB). It is recommended that the HPFW distribution 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 39 levels.

It is important to note that these RT 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 workers with longer response times.

HPFW RT 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 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 (response time) 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 (response time) is between 0 and 350 s.
This can be used for main buildings up to Level 38 (39 levels).

3. Generalised walking speeds of workers on ladders, temporary stairs and four different types of 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 or descent speed of workers on ladders will be slower than that on stairs, the level of the reduction has not been quantified. Similarly, it is generally assumed that ascent and descent speeds of workers on temporary scaffold stairs are identical to those 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 and descent speeds on temporary stairs and ladders and in the process uncovered a number of important and useful results.

As part of this project, generalised walking speeds for workers ascending and descending ladders and temporary scaffold stairs have been determined. The average ascent speed of workers on temporary scaffold dog-leg stairs and standard building stairs are very similar while the average descent speed is 84% of the corresponding building stair speed. The device with the next fastest performance in both ascent and descent is the parallel stair, with the ladder resulting in 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. For ladders, the average descent and ascent speeds are 52% and 67% of the corresponding normal building stair speeds. The slower ascent and descent speeds on these vertical access devices are 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, but 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 dog-leg 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 (consisting of nine treads) 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 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 (two directions), 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 (based on the number of months working on construction sites), where inexperienced workers (defined as having less than one month experience) 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 reduction factors associated with inexperienced workers 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 are an important consideration when determining maximum permissible travel distances and the time required by individuals to escape from high-rise construction sites.

4. Validation analysis

Before evacuation modelling tools can be applied reliably to high-rise construction sites they need to undergo some form of validation to demonstrate that they can appropriately take into consideration the unique features associated with construction site evacuation. As part of this project, a validation data-set has been defined, describing the evacuation of a high-rise construction site consisting of 227 workers distributed over 35 levels. While there are several uncertainties concerning some initial conditions associated with the data-set, it was considered acceptable for use in assessing the performance of evacuation simulation software. The average exit curve, produced by 100 repeat simulations of the building EXODUS 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 of 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. Use of the validated evacuation model to explore improvements in evacuation performance

One of the benefits of validated evacuation models for high-rise construction sites is that they can be used to explore the impact of alternative means of evacuation and innovative procedures for evacuation in a systematic and reliable manner. As part of this project 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 400 workers located in the main building and 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.

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 the stairs only case, if 100% of the population used the hoists.
- Evacuation efficiency increases with construction height when 100% of the population used hoists.
- If 50% of the population use the hoists, evacuation times increase compared to the 100% hoist usage case, 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 population 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 would be increased by 16%.

What does the research mean?

The project has developed a unique evidence base characterising, for the first time, the actual performance and behaviour of construction workers during emergency evacuation. The evidence base 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 dog-leg and parallel scaffold stairs and ladders. The data have 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.

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 limitations, assumptions and omissions in guidelines and regulations, including those produced by the Health and Safety Executive, 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.

Don't forget...

As in any study there are limitations imposed on the findings due to practical constraints in collecting data and in performing the various analysis presented in this document. In interpreting the results presented in this work it is important to take the following constraints into consideration.

- 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.

- 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. A lack of data from these types of activities may result in extremely long response times being excluded from the proposed data-sets.
- 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.
- Data from questionnaires represent only 7% of the population that evacuated during the four trials, with all the data being generated from only two trials. However, the data does represent information from 27% of the people who evacuated from these two trials.
- There is 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.
- For all the suggested improvements investigated using the validated evacuation simulation software, 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 workers), 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 may be required.
- When assessing the impact of using hoists to assist with 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 may 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 affect the efficiency of using the hoist for evacuation.
- When assessing the impact of using the hoists to assist in evacuation, the potential impact of fire and smoke was not taken into consideration.

Our summary gives you all the major findings of the independent study by the University of Greenwich. If you want to read about the study in more depth, you can download the full report from www.iosh.com/constructionevacuation

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