Construction Site Evacuation Safety

Evacuation strategies for tall construction sites

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Acknowledgements

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  - The FSEG team who worked on the project, Mr David Cooney, Dr Steve Deere, Prof Ed Galea, Dr Lynn Hulse, Dr Peter Lawrence and Dr Hui Xie.
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- Special thanks to the 1078 construction site workers from 22 and 100 Bishopsgate who generously gave their time during the four evacuation trials and five walking speed experiments.

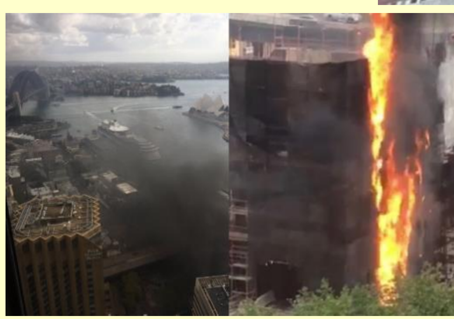
Construction Sites – Potential for mass evacuation

- In London over 500 high-rise building projects planned (2019)
  - Hundreds of workers may be on a site at any one time
- Thousands of construction site fires reported each year in UK.
- While construction site fires in the UK have not resulted in large loss of life in recent years, there is clearly significant potential.

Fountain Views Tower
Dubai, UAE,
02 April 2017

Warsaw Hub, Poland
8 June 2019

Belway
Homes UK
2008



Circular Quay Sydney,
Australia 13 Feb 2018

Incheon South Korea
38 workers killed
29 April 2020

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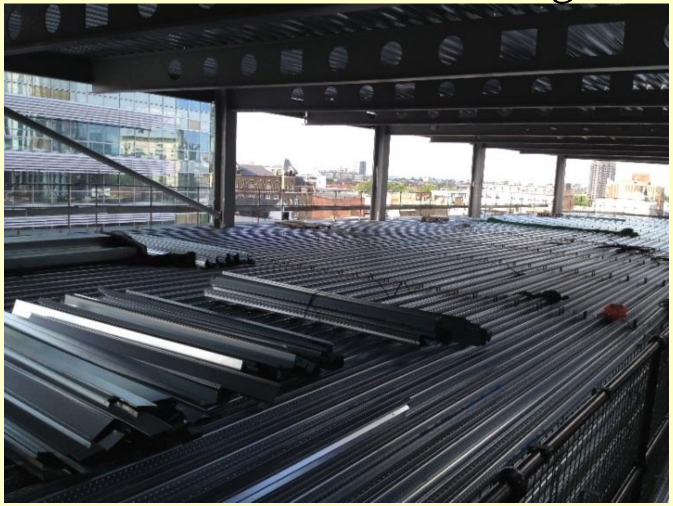
Examples of Current Health and Safety Guidance

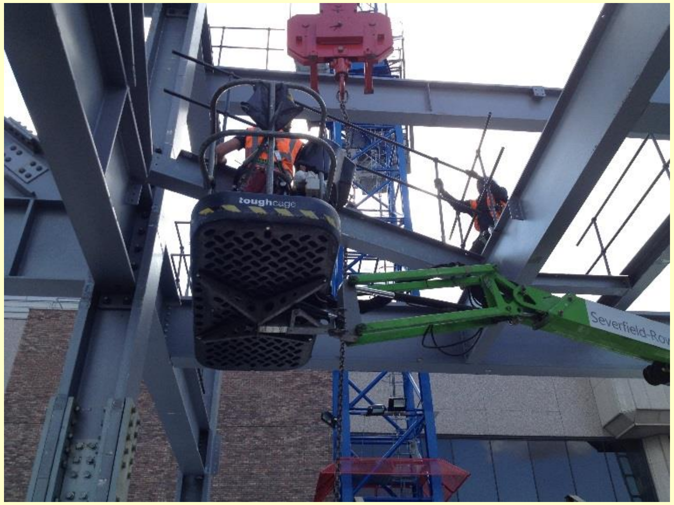
- **HSE, The Regulatory Reform (Fire Safety) Order 2005 (FSO)**
  - **Regulation 15**. Procedures for serious and imminent danger and for danger areas (Page 12)
    – "…the procedures … must enable the persons concerned …… ***in the absence of guidance or instruction*** **………** to ***stop work and immediately proceed*** to a place of safety in the event of their being exposed to ….unavoidable danger."
- **HSE, Health and safety in construction HSG150 (Third edition) HSE Books 2006 ISBN 978 0 7176 6182 2**
  - **Stairways, external escape stairs and ladders**: 197- 201, 206, 207 (Page 36-38)
    – "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*** *…"*
    – "…***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. "
- **HSE, Fire safety in construction work HSG168 HSE Books (Second edition)**
  - **Travel distance:** 190 – 196 (Page 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*** …"

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

Construction Site Evacuation - Challenges

- Does not have fire engineered evacuation solution
- Not governed by evacuation regulations.
- Physical layout constantly changing making wayfinding difficult and requiring evacuation routes to be constantly updated
- Floor surfaces can be physically challenging hindering rapid movement.
- Some activities must be made safe prior to evacuation.
- Noise on site and working at height.



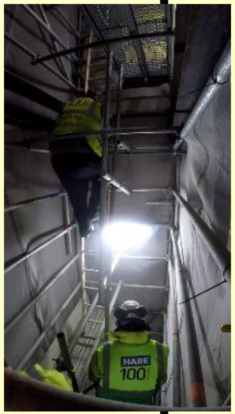


- 2 High-rise Construction sites
- 4 Evacuation Trials

iosh

MULTIPLEX
Built to outperform.

Three Key Areas of Construction



Formworks

Core

Partially completed floors

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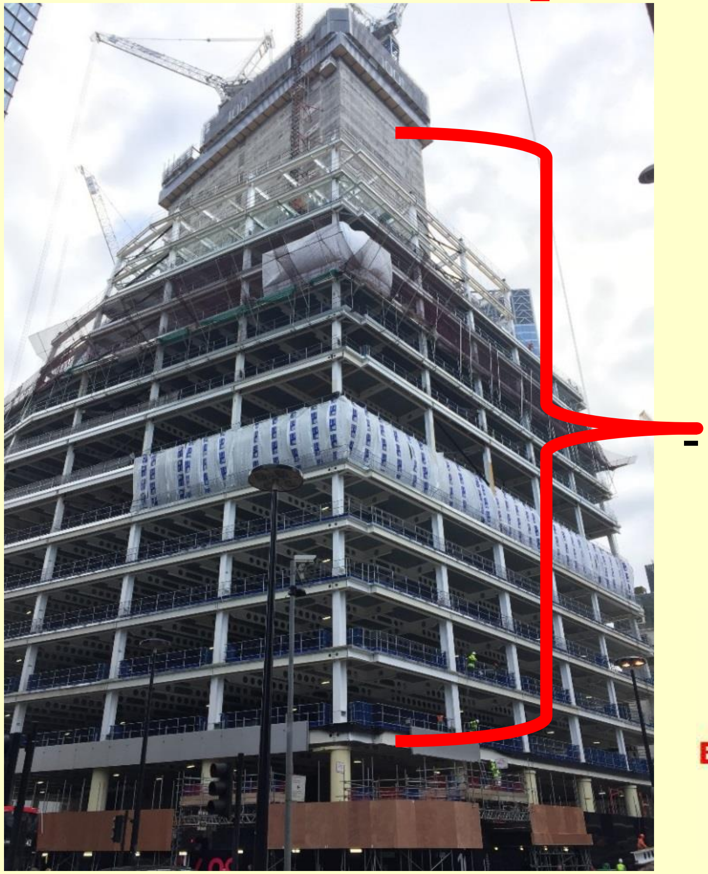
Worker Questionnaires

- 7% (61) of participants from the four trials provided useable replies
  - These represented 27% of the participants from the first two trials.
- 62% reported that they thought the alarm represented a real emergency.
- **Delays in Evacuation Response:**
- 82% knew that they had to evacuate immediately on hearing alarm
  - However, only 49% reported their first action on hearing alarm was to start to evacuate.
- 80% claimed they were prompted by alarm and did not require staff intervention
  - However, video evidence suggests between 43% and 70% required staff intervention
  - Highlights the need for, and importance of, assertive supervisors.
  - Begs the question - Do workers understand what 'evacuate immediately' means?
  - May require enhanced training and/or greater enforcement of the policy by supervisors.
- Workers perceived that employers find it more important than they to complete their tasks prior to evacuating.
  - Mixed messages concerning importance of immediate evacuation requiring improvements in safety culture.
  - May explain long response times

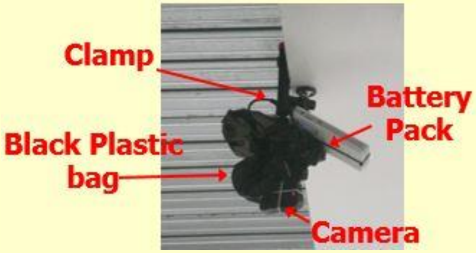
Worker Questionnaires

- **Risk Perception:**
- Workers appetite for risk comparable with the average person,
- Also perceive that they are in a safe environment while on their construction site.
  - However construction sites are inherently hazardous environments.
  - Risk of complacency in worker response to potentially hazardous situations.
  - Training should develop understanding of how quickly emergency situations can deteriorate, reinforcing the messages that ‘every second counts’ and ‘immediately’ means disengaging from pre-alarm activities as soon as alarm sounds.
  - May explain RT observations concerning height of construction.
- **Exit Knowledge:**
- 33% knew the exit route,
- 21% looked for emergency exit signage
- 13% followed others
- 10% took the same route as they used to enter.
- 3% sought advice from a supervisor.
- High proportion of workers reliant on exit signage highlights the importance of up-to-date and prominent emergency exit signage on site.
- ***No significant difference between native and non-native English speakers.***

How long does it take workers in the Main Building to respond to the alarm?



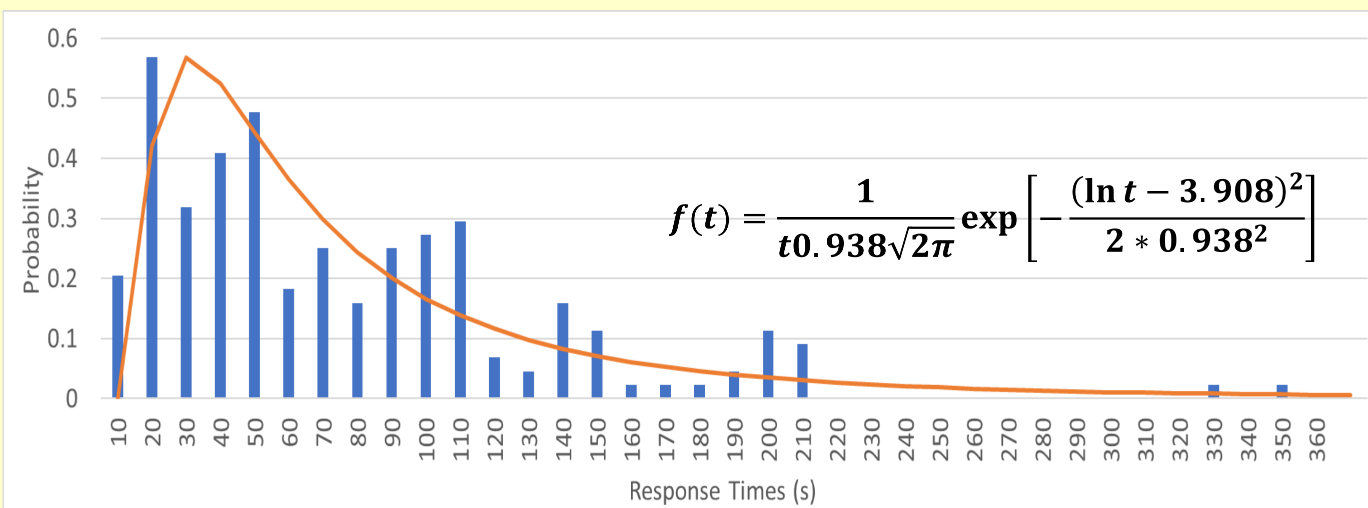
Main building
- Core and partially completed floors above ground level



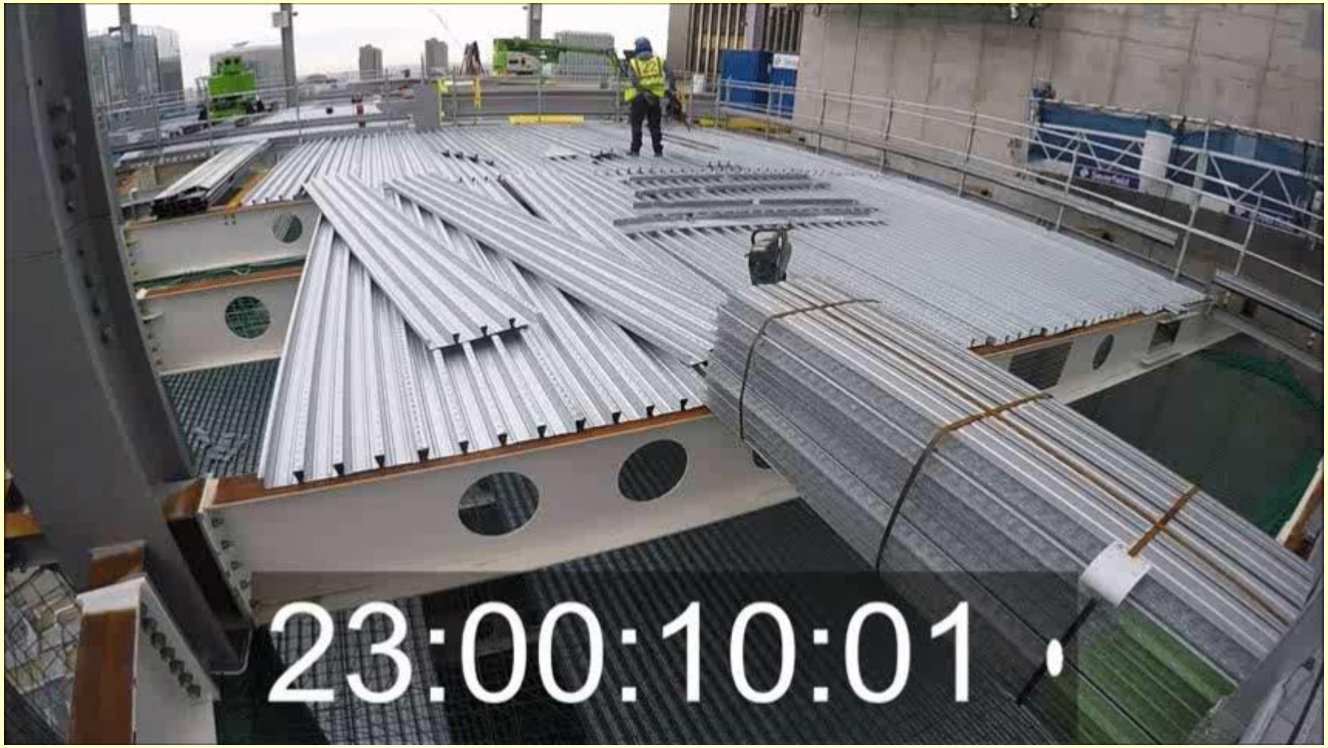
30 GoPro cameras strategically placed

Combined Response Time Distribution for Main Building

- Data from three trials and two building sites - 156 data points in total.
- Typical log-normal distribution found in evacuation of all building types
  - **Mean: 1.2 min**, **Max: 5.7 min**, complete average of 2.2 tasks b4 evacuating
- 48% disengage < 40 s, 41% undertake ≤ 1 preparation task b4 evacuating
- 32% disengage > 60 s, 23% undertake ≥ 4 preparation task b4 evacuating
  - Explains long response times.
- NOTE: Data excludes crane operators and concrete pours – may extend RT even further.



Exceptionally Long Response Times



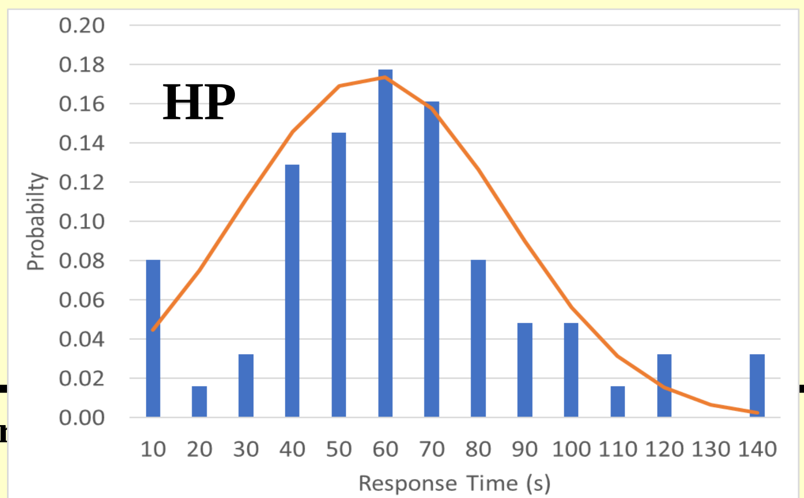
- Isolated worker
- Wearing ear protectors
  - These conditions result in prolonged response times
  - This person required 5.7 min to respond to the alarm
- Requires assertive staff intervention and well trained supervisors
- Technological solutions such as phone apps or vibrating personal alarms

How long does it take workers in the FW to respond?

- Two types of main activity noted:
  - **High Priority:** time critical, just prior to concrete pour e.g. installing shutters
    - Trial 2 and 4 (22 BG)
  - **Low Priority:** just after a concrete pour e.g. dismantling shutters.
    - Trial 1 (100 BG):

Combined Response Time Distribution for the Formworks

- **FW RT dependent on phase of work.**
- **Requires two RTDs, one for HP work and one for LP work**
- Low Priority (LP) activities in Trial 1, 19 data points in total
  - RTD different to MB.
  - Normal distribution, Mean: 0.48 min and Max: 0.85 min.
  - Workers react ***very rapidly*** compared to MB.
- High Priority (HP) activities in Trials 2 and 4, 60 data points in total
  - RTD different to MB ***and*** different to LP FW.
  - Normal distribution, Mean: 0.95 min and Max: 2.2 min.
  - Workers react rapidly compared to MB but slower then in LP work situation
- **NOTE: Data excludes extremely high priority activities i.e. concrete pour**



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

Is RT Dependent on Height of Construction?

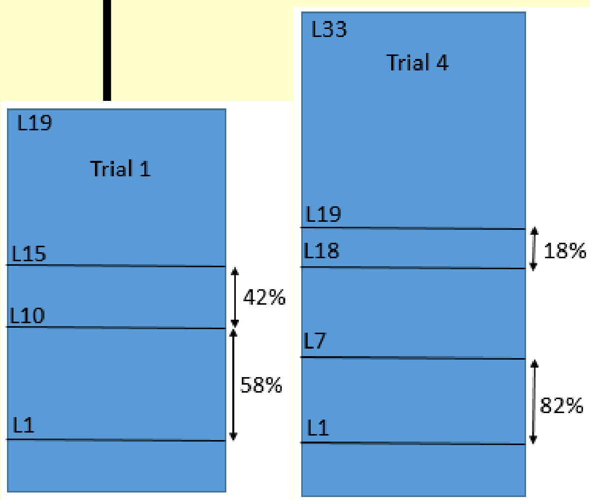
38 Levels

18 Levels

7 Levels

Comparing MB RT Distributions

- Compare MB RT distributions for Trials 1, 3 and 4
  - Independent two Tail T Test, 95% confidence level
  - All 3 RTD are from statistically identical distributions.

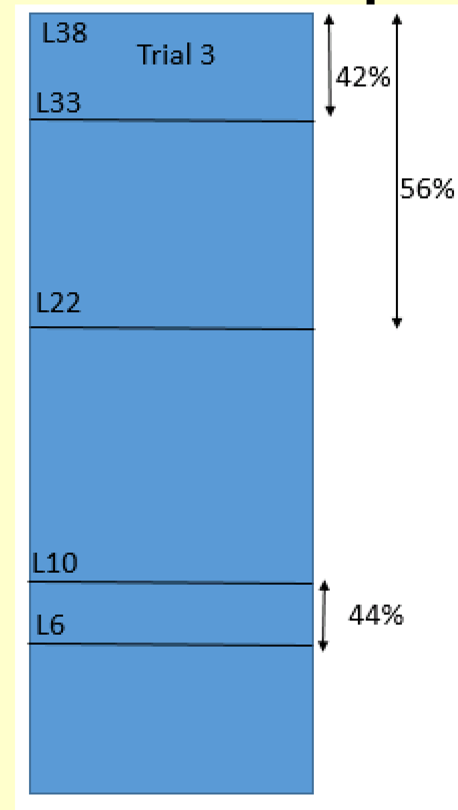


Trial 1 (low) vs **Trial 3 (high)**

T Test suggests distributions are identical (p = 0.64).

Trial 4 (low) vs **Trial 3 (high)**

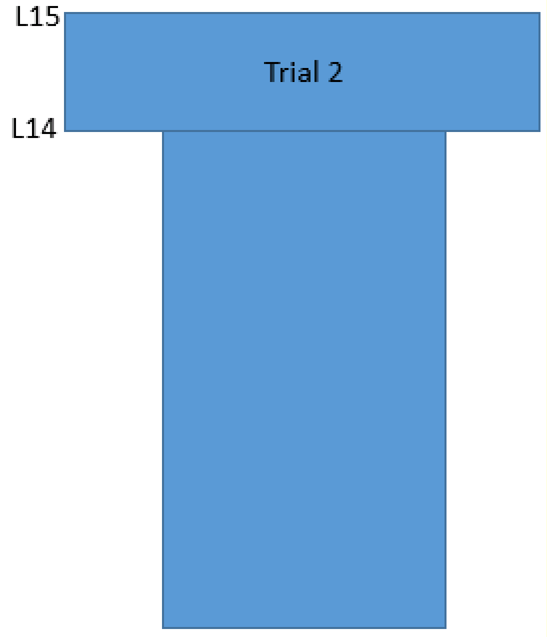
T Test suggests distributions are identical (p = 0.3)



- **Up to 39 levels, height does not appear to influence RT distribution within the main building.**
- Risk Perception? From questionnaire, workers perceive that they are in a safe environment while on their construction site

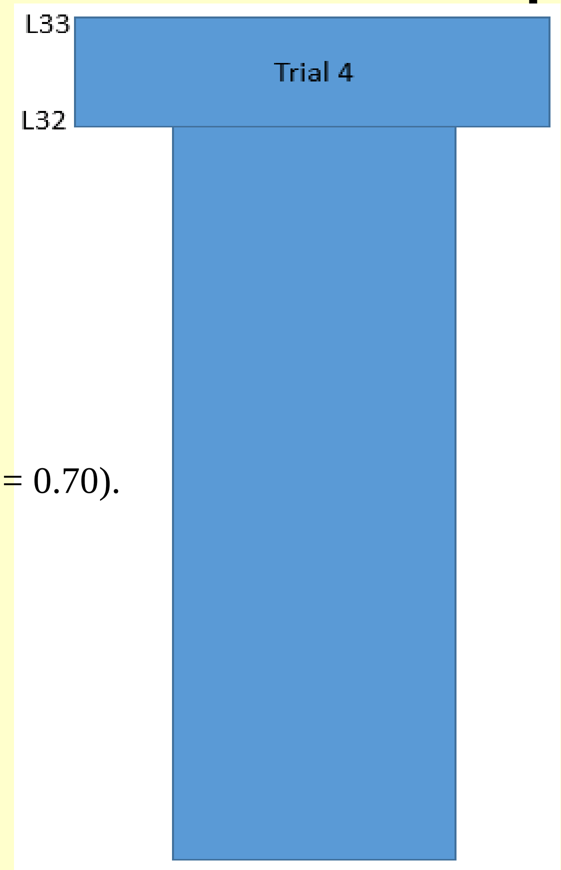
Comparing FW RT Distributions

- Compare FW RT distributions for Trials 2 and 4
  - Independent two Tail T Test, 95% confidence level
  - Both RTD are from statistically identical distributions.



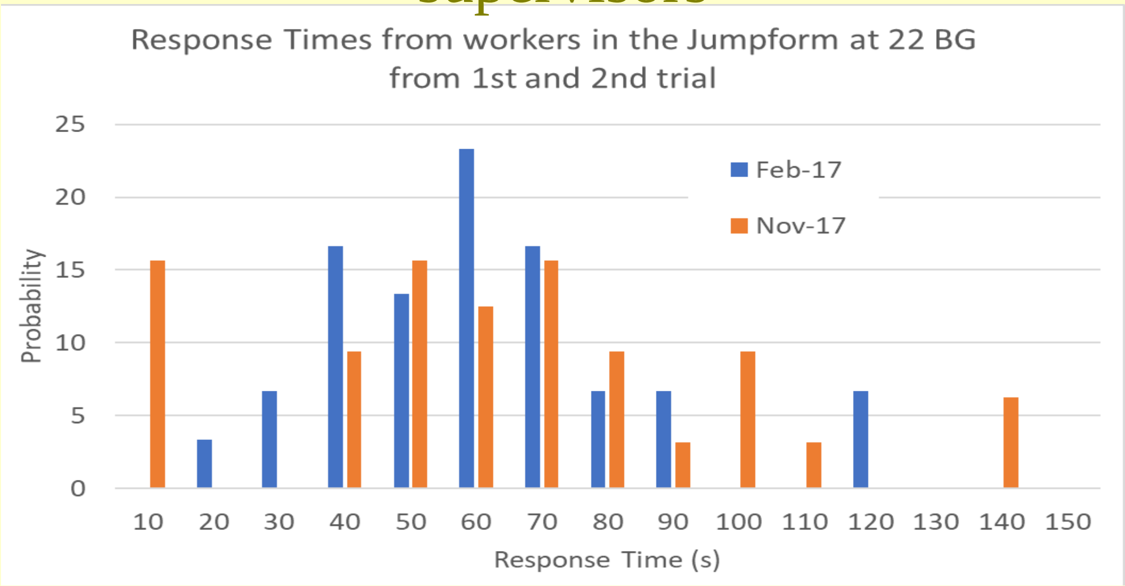
Trial 2 (low) vs **Trial 4 (high)**

T Test suggests distributions are identical (p = 0.70).



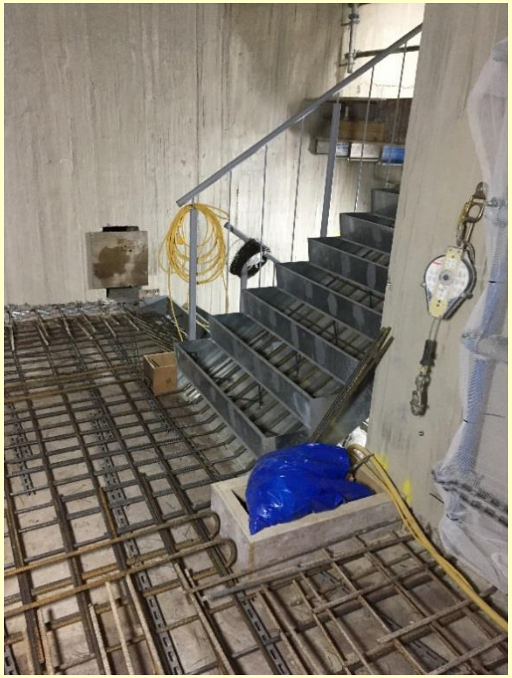
- **For FW up to 34 levels high, height does not appear to influence RT distribution within the FW.**

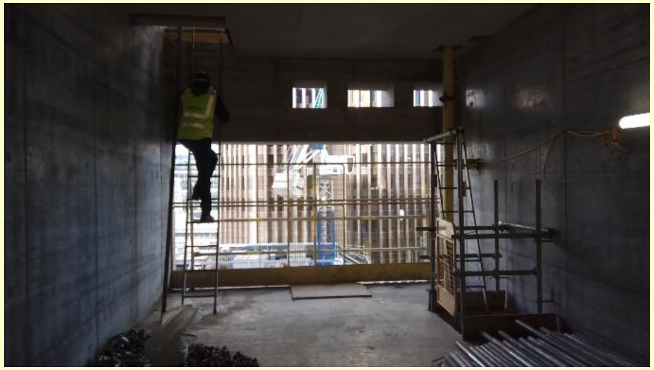
RT distribution for Formworks (22BG) Trial 2 & 4 excluding supervisors



- Excluding supervisors, RT distributions look very similar.
- Unlike most RT distributions, these appear to follow normal distributions
  - Shapiro-Wilks test confirmed both distributions are normal (28 & 32 data points, p=0.12 & 0.26)
- T Test suggests distributions are identical (P = 0.7 at 99% confidence level).
- Hence can combine both RT distributions to form definitive RT distribution which is also normal (Shapiro-Wilks test confirms).
- Building height does not appear to impact RT distribution (17 and 34 floors)

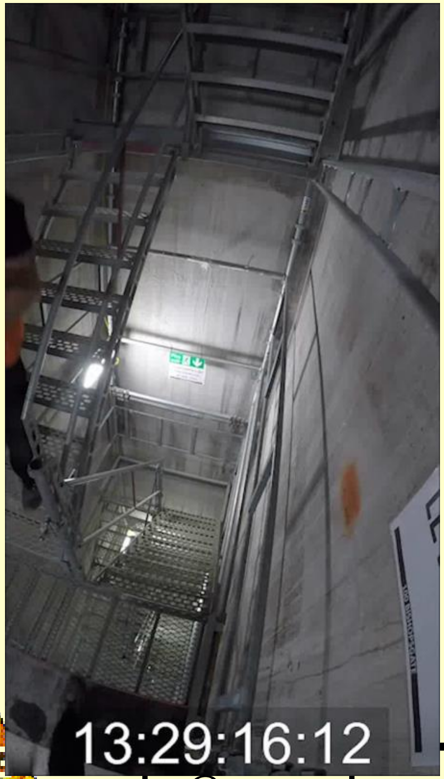
The Impact of Temporary Scaffold Stairs and Ladders on Vertical Speeds





Scaffold Stairs

- Two types of scaffold stairs typically used on the construction sites.
- Dog-Leg stairs: each flight is off-set by a landing
  - Data points: 73 down, 69 up
- Parallel stairs: each flight is arranged on top of each other resulting in limited head clearance per flight – impacts travel speed.
  - Data points: 53 down, 53 up



Dog-leg stair down

Parallel stair down

Ladders vs Dog-leg vs Parallel vs Building Stairs

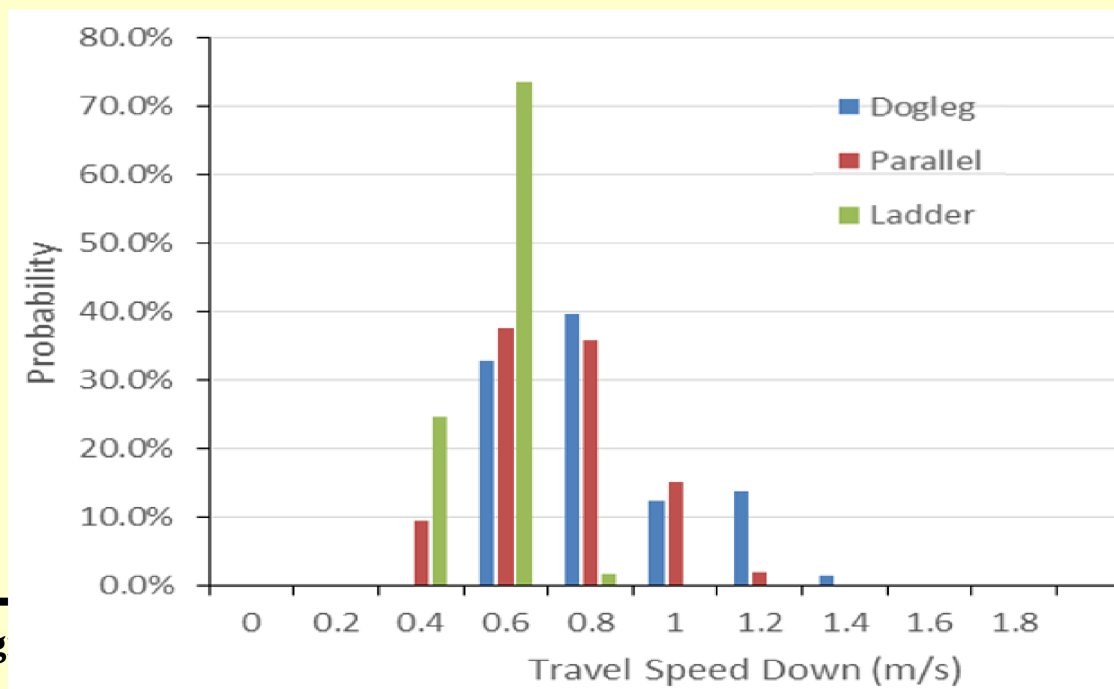
- Ladders are clearly a bottleneck in any evacuation route and their use should be limited

Descending

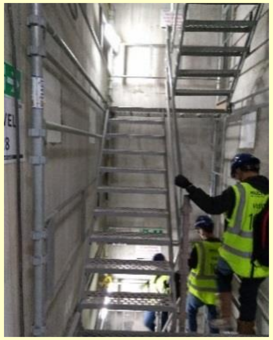
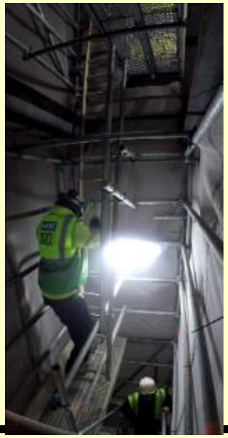
	Dogleg stairs (m/s)	Parallel stairs (m/s)	Ladder (m/s)	Standard stairs average (Fruin) (m/s)
Min	0.42	0.36	0.29	(Male 51–80) 0.67
Average	0.72	0.64	0.45	(Male 30–50) 0.86
Max	1.21	1.15	0.61	(Male 17–29) 1.01

Ascending

	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



Average performance of Ladders, Dog-leg and Parallel stairs vs Building Stairs

	Descending	Ascending
	84% of stair average	Equivalent to stair average
	74% of stair average	79% of stair average
	52% of stair average	67% of stair average

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The Impact of Floor Surface on Walking Speeds

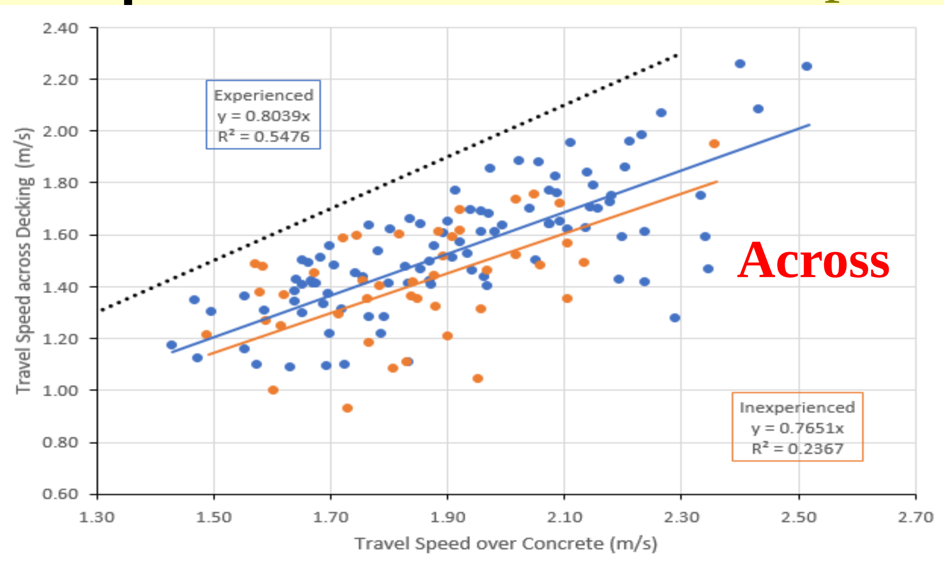
Concrete surface 144 data points

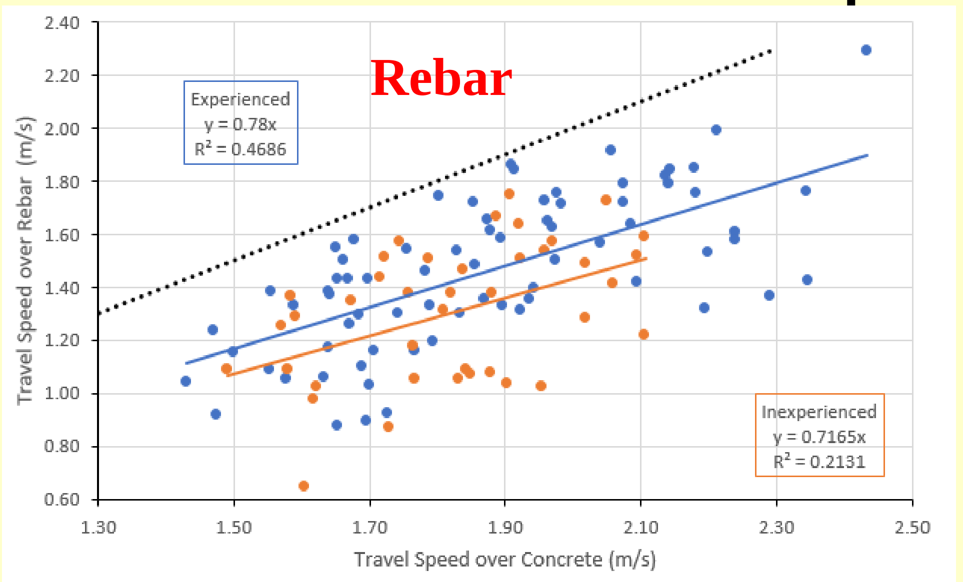
Along (143 data points) and across (142 data points) decking

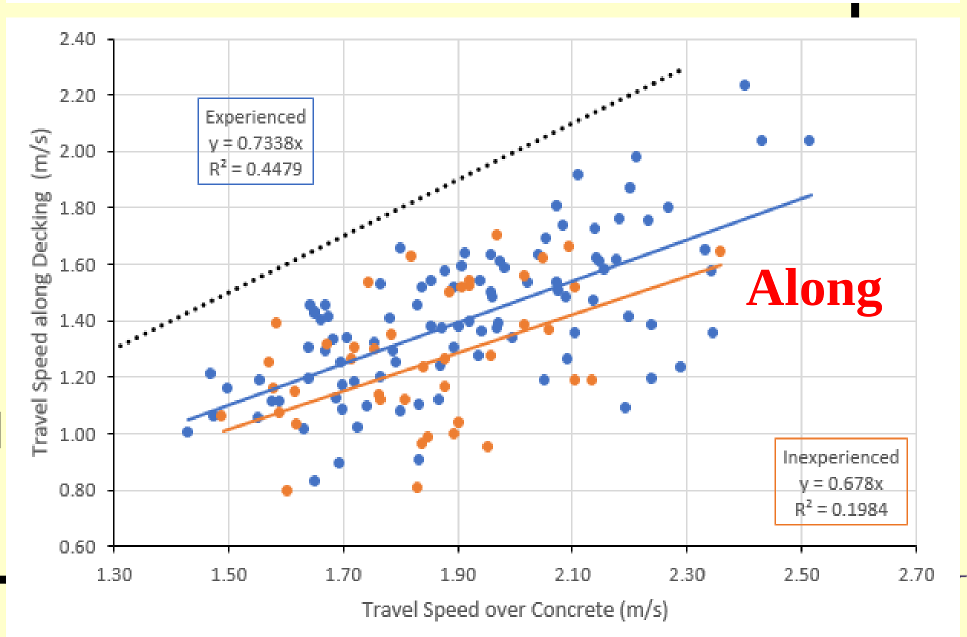
Decking with Rebar (116 data points)

- 545 walking speed data points collected

Travel Speed Trials Results







- Speeds dependent on experience on sites
- Critical level ~ 1 month exposure
- Generally Speeds follow trend:
  - Concrete > Across Decking > Rebar > Along decking
  - But large variation.
- Experience speed > inexperienced
- Speed reduction can be as much as 30%

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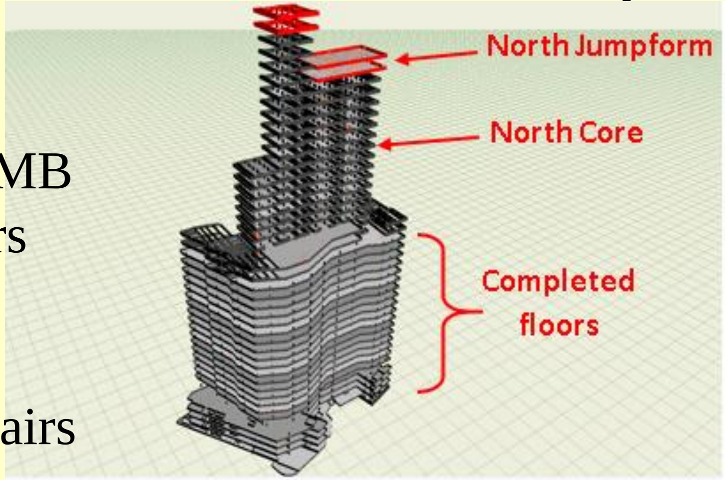
Travel Speed Trials Results

Inexperienced: less than 1 month exposure

Validating the buildingEXODUS Evacuation Model for Construction Site Applications

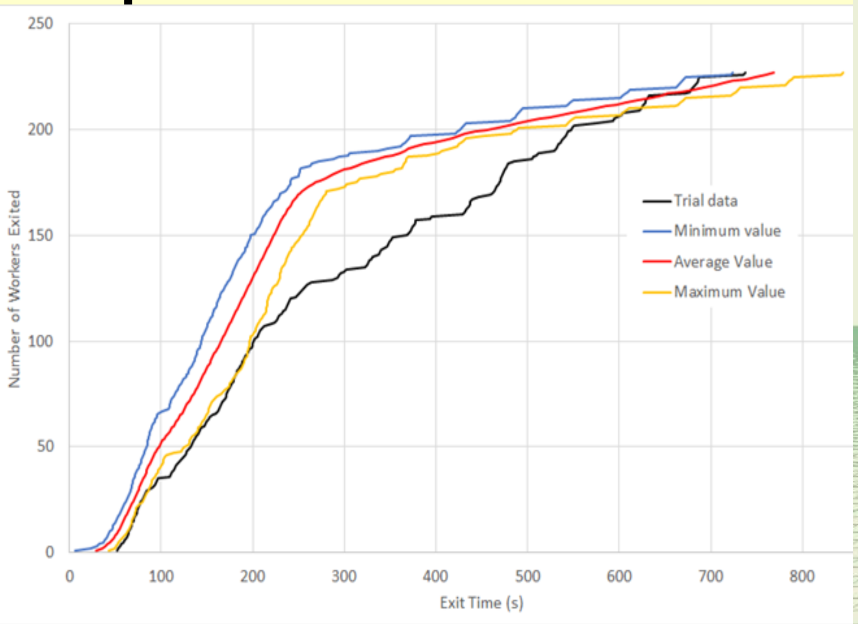
Validation Case – 22 BG

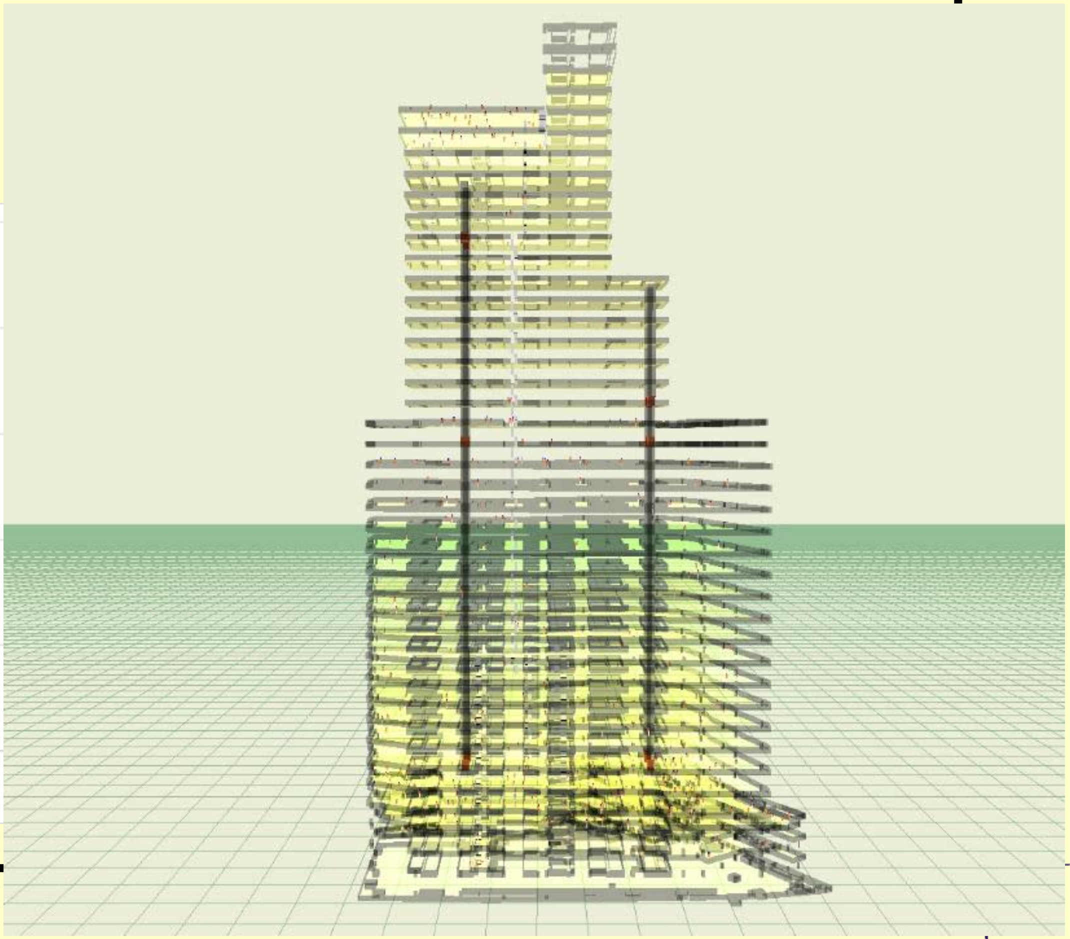


- Geometry: MB: L3 to L32; FW: L33 to L34
- Population: MB: 190; FW: 37
- Ladders in the FW, scaffold dog-leg stairs in MB
- Decking and decking and rebar on some floors
- buildingEXODUS software modified:
  - Includes ability to identify floor surfaces
  - Includes ability to represent temporary stairs and ladders
  - Includes data-set for floors surfaces, temporary stairs, ladders and response times.
- Run 100 repeat simulations
- Compare average results with experimental curve
- Note that omissions in data-set mean that precise agreement unlikely.
- Omissions include:
  - exact starting location of workers on each floor
  - Presence of clutter on each floor
- Attempt to achieve 'reasonable' agreement with data-set

Validation Average Results

- FW clearance: average predicted: 160 s; Trial: 189 s; - 15%.
- MB clearance: average predicted: 769 s; Trial: 737 s; + 4%.
- Time for 50% exit (113 people):
  - average predicted: 180 s; Trial: 232 s; -22%





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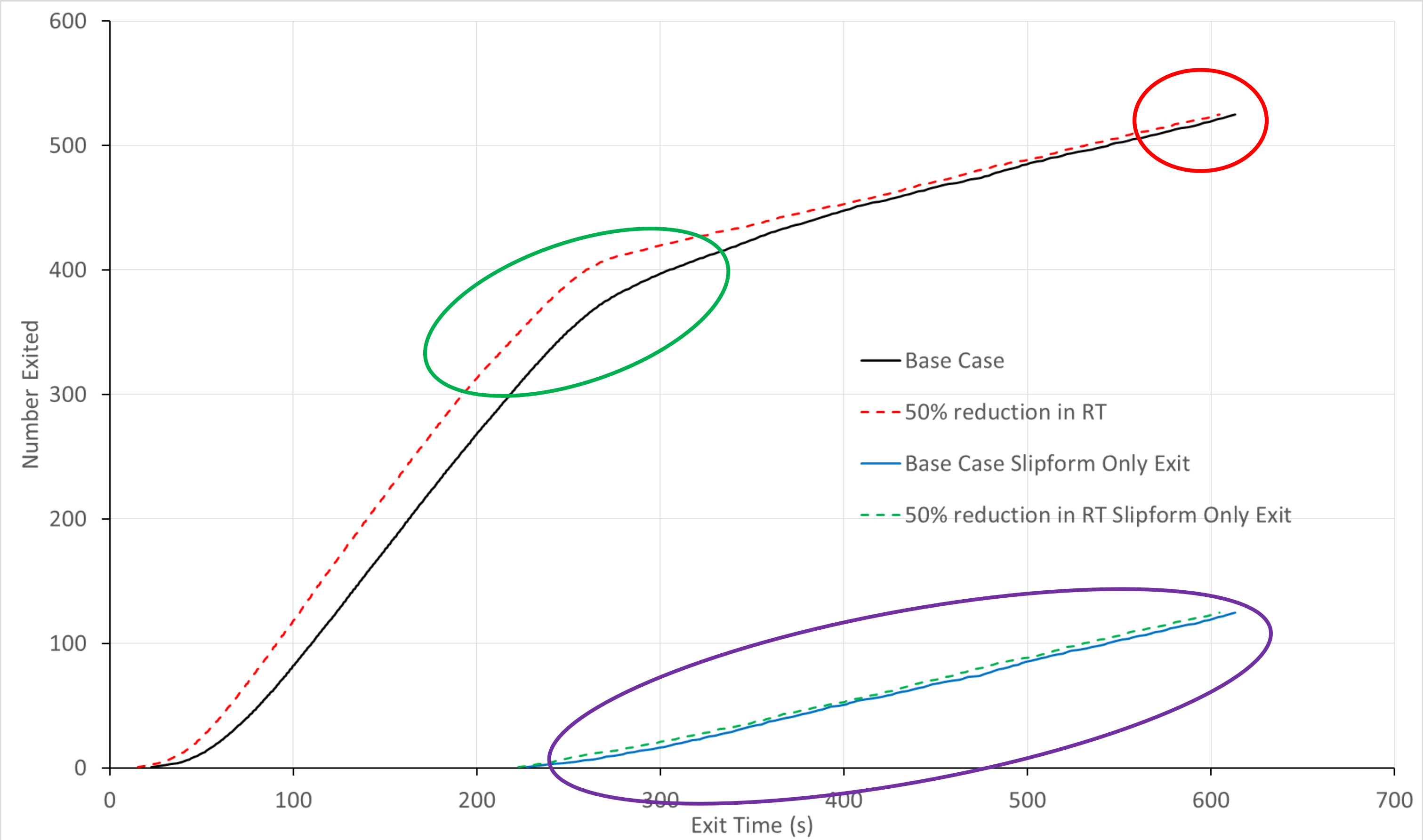
Exploring Potential Improvements in Construction Site Evacuation using Modelling

Two Benchmark models (BM) representing 100 BG

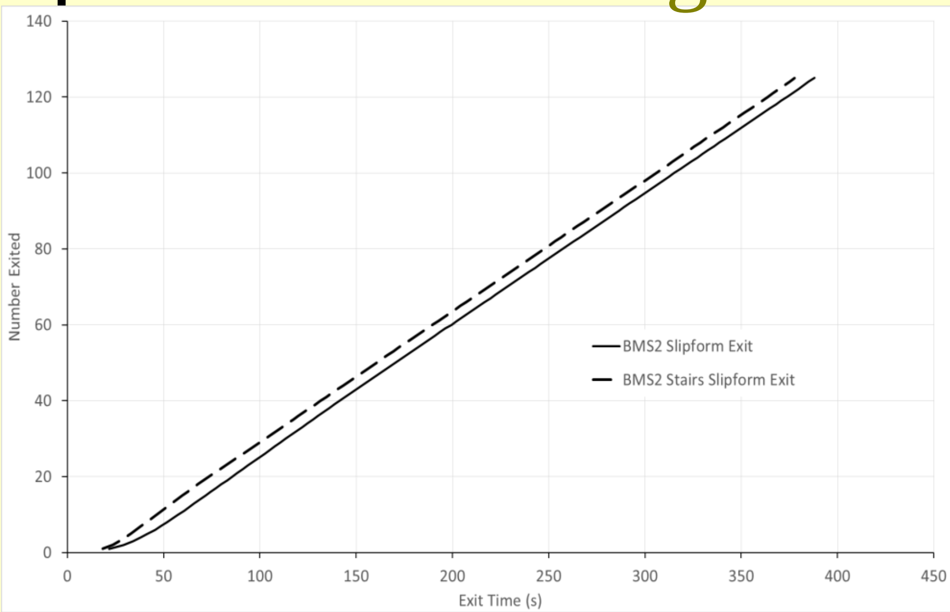
- MB population: 400 agents
- FW population: 125 agents
- 8 hoists are available
- Assume MB RTD and HPFW RTD
- BM1: 23 levels
- BM2: 43 levels

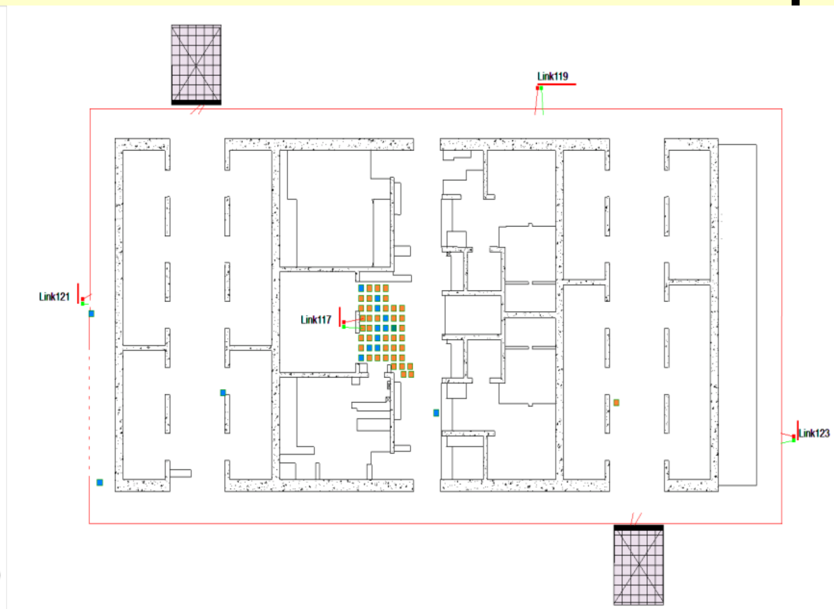
BM1 impact of 50% Reduction in RT



- Overall building evacuation time reduced by only 1%
- However, evacuation time for MB pop is reduced by 33%
- Poor overall improvement due to performance of FW workers.

BM1 impact of 50% Reduction in RT – congestion in the FW

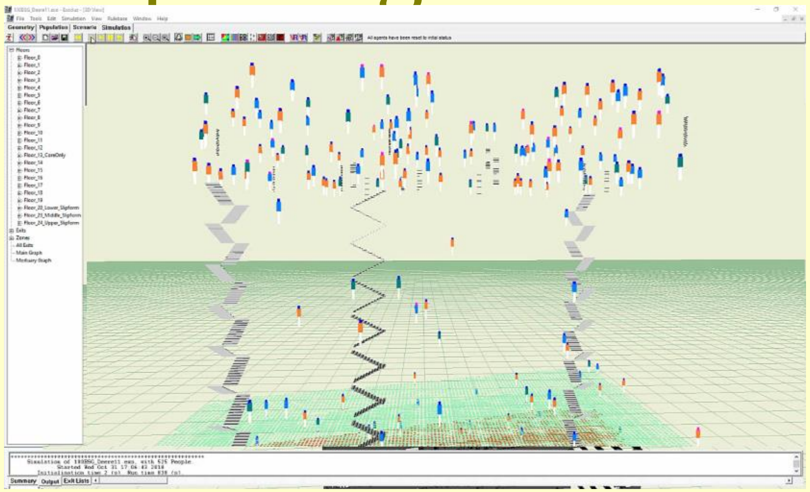




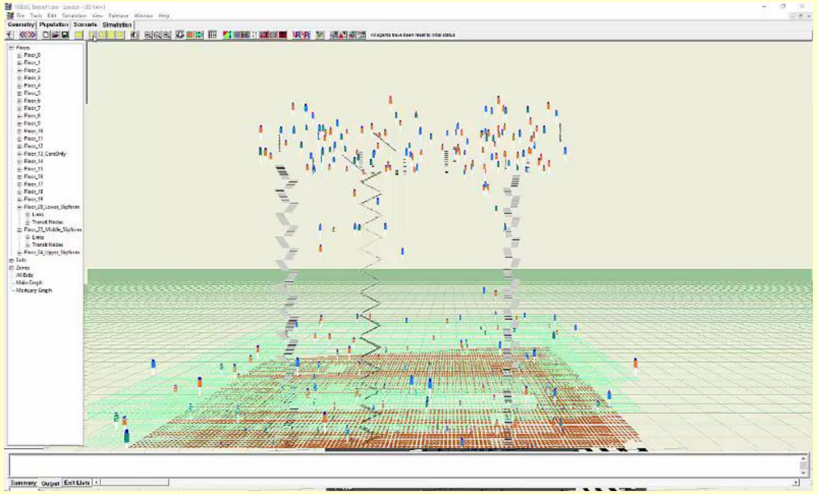
	Upper Deck				Middle Deck			
	Start Time (s)	Most severe (s)	End Time (s)	No. of agents	Start Time (s)	Most severe (s)	End Time (s)	No. of agents
Ladders	35	146	311	49	45	177	376	25

- Poor overall performance due to congestion in the FW
- Only exit is via a single ladder
- Severe congestion at the entrance to the exit ladder on each deck.

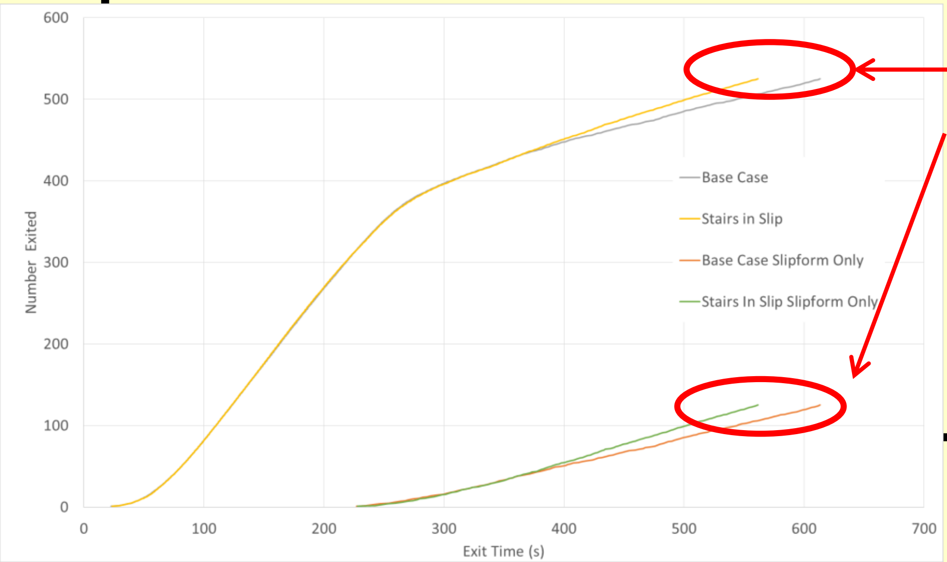
Replacing FW ladders with scaffold stairs



BM1 125 workers in FW: *6 m 27 s* to clear FW with ladders, Time to clear building: *10 m 13 s*



BM1 125 workers in FW: *5 m 20 s* to clear FW with dogleg scaffold stairs, Time to clear building: *9 m 21 s*



- 9% reduction in TET
- 17% reduction in time to clear FW
- While improved, FW exit still congested due to single means of escape.
- To reduce further, add a 2nd stair

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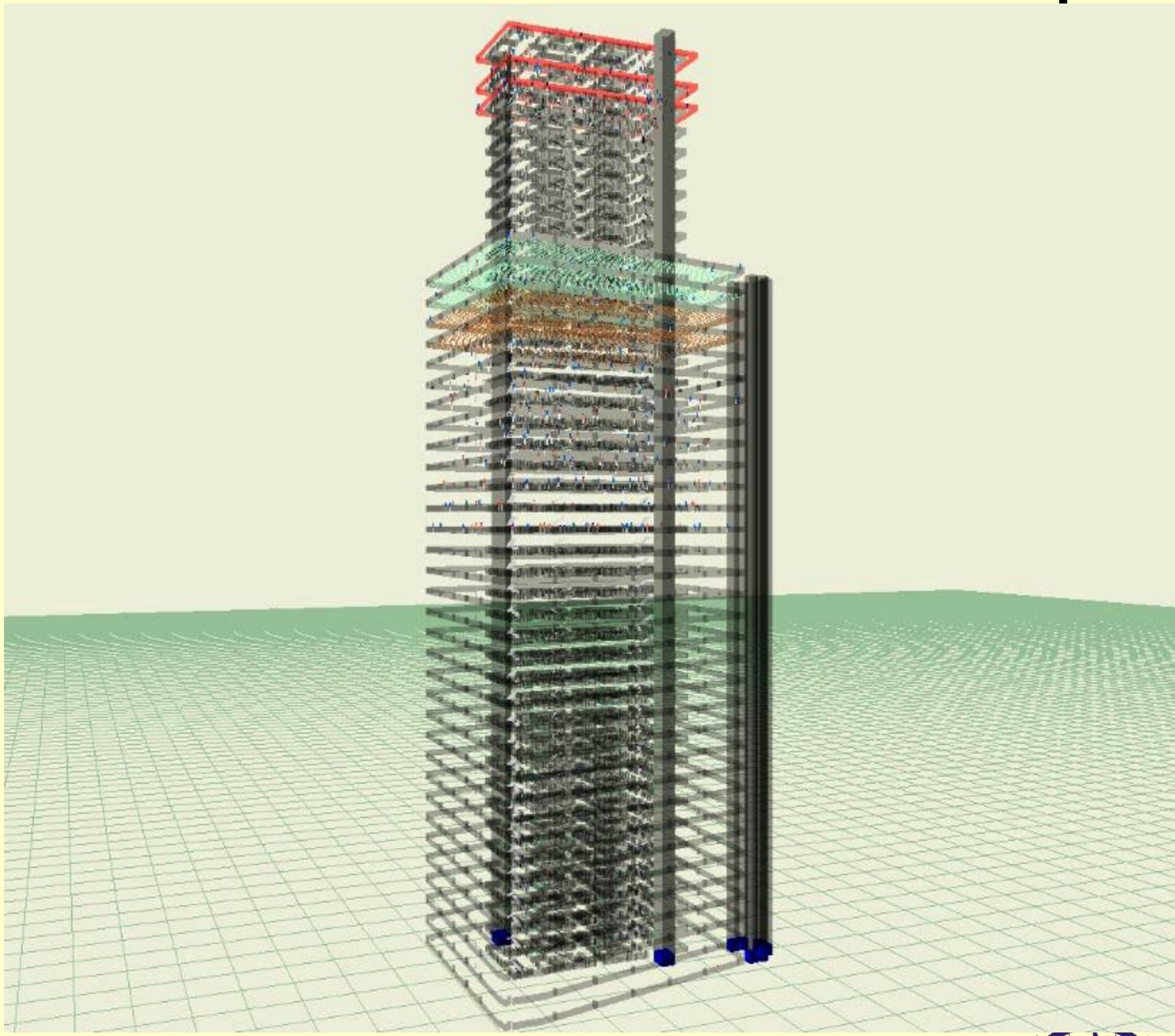
Use of Hoists for General Evacuation

- Two building heights considered, BM1 and BM2.
- Two hoist speeds considered, (1.5 m/s and 0.7 m/s)
- Two hoist capacities considered (40 and 30 occupants).
- Single dispatch scenario considered
  - 2 hoists serve FW
  - 6 hoists serve MB
- Two cases considered, 100% hoist usage and 50:50 hoist:stair usage



Use of Hoists for General Evacuation

- Findings are dependent on the nature of the dispatch strategy applied.
- Presented results apply only to the specific dispatch strategy used in study

- Fast hoists high capacity
  - Significant benefits
  - Regardless of height
  - Even partial use of hoists advantageous

- Slow hoists high capacity
  - Marginal benefit
  - Particularly for lower buildings

- Slow hoists low capacity
  - Do not use hoists
  - Especially for higher buildings

Fast Hoists with High Capacity			
Height of construction	Stairs Only	Hoist Only	50/50 Stairs/Hoist
23 Levels	615 s	25% (463 s)	23% (471 s)
43 Levels	852 s	30% (592 s)	19% (692 s)

Slow Hoists with High Capacity			
Height of construction	Stairs Only	Hoist Only	50/50 Stairs/Hoist
23 Levels	615 s	4% (589 s)	7% (570 s)
43 Levels	852 s	-26% (1078 s)	4% (821 s)

Slow Hoists with Low Capacity			
Height of construction	Stairs Only	Hoist Only	50/50 Stairs/Hoist
23 Levels	615 s	-37% (845 s)	8% (568 s)
43 Levels	852 s	-80% (1530 s)	-16% (991 s)

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CONCLUDING COMMENTS

- It is hoped that these findings will advance the safety of construction workers by:
  - Addressing the limitations, assumptions and omissions in guidelines and regulations, through the incorporation of the evidence base.
  - Informing worker training and formulation of best practice.
  - Encouraging the application of suitably validated evacuation models to define and refine enhanced evacuation procedures.

- In this way the work environment for construction workers will be improved through better preparation for, and management of, on-site emergency evacuation.

What do we do with these findings?

- How can the industry benefit from the evidence base and the validated modelling tools produced by FSEG?
  - More realistic assumptions can be imposed on updated version of HSG168,
  - Safety managers can make use of evidence based planning for emergency response,
  - Evidence based approach to modification of evacuation planning for different phases of construction (travel speeds on different surfaces, stairs, scaffold stairs (dog-leg and parallel), ladders etc),
  - The part that Hoist/Lifts can play,
  - Use of validated evacuation software to assist in evacuation planning,
  - The importance of management and supervision,
  - More targeted evacuation training addressing identified issues.

USEFUL LINKS

- The full report can be downloaded from the IOSH website: www.iosh.com/constructionevacuation
- Construction site evacuation simulation videos can be found on the FSEG YOUTUBE Channel at the following playlist: https://www.youtube.com/playlist?list=PL07Y9xXpCDutNe8W10aIr6NJh7aAeEZa0
- Overview of the project from the FSEG web pages at: https://fseg.gre.ac.uk/fire/construction_sites123.html
- The High-Rise Construction Site Evacuation Modelling Validation Data-Set can be downloaded from: http://fseg.gre.ac.uk/validation/building_evacuation/

Thanks to the SFPE UK Branch

"Outstanding, unique and informative research in an area seldom explored. There is great potential to make the construction environment and all those who work in it safer from fire and this research provides data and tools to achieve this objective." SFPE