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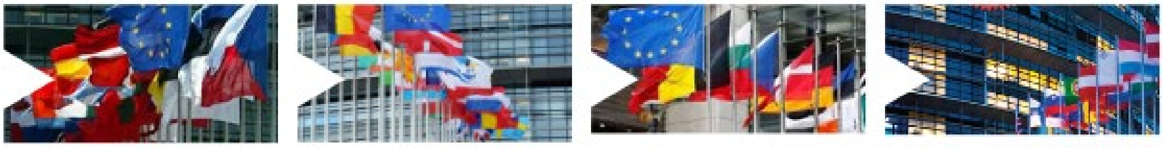

Q3 2020 ISSUE 19

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A FAÇADE OF FIRE SAFETY

By Birgitte Messerschmidt, Director Applied Research, NFPA, USA

What's the problem?

Since the energy crisis in the early 1970ies there has been an interest in making buildings more energy efficient. This has caused a significant increase in the requirements to the thermal performance of exterior walls leading to extensive use of insulated exterior walls. There are several different ways to make an insulated exterior wall. The most frequently used systems include ETICS (External Insulating Composite System)/ EIFS (external Insulating Façade System) which consist of a layer of insulation, a reinforced mesh layer, and a thin coating of exterior material—as well as the ventilated façade system, where an air gap of at least 25 mm between the insulation and the covering panels allows moisture to escape. The insulation used in these systems can be combustible (such as Polystyrene, Polyurethane and Polyisocyanurate) or non-combustible (including stone wool, glass wool and Foam Glass). Price, weight, and thermal performance often makes combustible insulation the preferred option. This choice comes with the inherent challenge of ensuring that it does not become involved in a fire. The covering used in ventilated facades also comes in many different versions, from inert natural stone to metal composite panels with combustible cores—again, spanning a vast range of potential risk in the event of fire. The ease with which these systems ignite and spread fire depends on the combustibility of the materials used and how the system is designed to limit ignition and fire spread.

While some experts were trying to warn about the potential risk of combustible façade systems it took many years before enough of these systems were in use for us to start to see their impact. Then we started to see more and more fires with a dramatically fast fire spread over the exterior of the building. According to research done at Imperial College in London [1], the frequency of façade fires in large buildings has increased by seven times in the last three decades. Surprisingly the only way that researchers know about this increase in these types of fires is from the media. There is no coordinated effort globally at this point to collect consistent and comparable data on these or any other fire incidents.

Despite the increase in number of fires involving combustible exterior walls the number of fatalities were low so even a report published by the Fire Protection Research Foundation in 2014 on Fire Hazards of Exterior Wall Assemblies Containing Combustible Components [2] providing insights into the potential dangers of these systems was not enough to inspire policy makers into action. It was not until the fire in Grenfell Tower on the night of June 14, 2017 claimed the lives of 72 people that the world woke up to the hazard presented by combustible exterior walls.

How is this regulated?

Most buildings codes and regulations attempt to control the fire performance of exterior walls through requirements to the fire performance of the façade system. While the safety objectives of these requirements are similar from country to country, the way they're carried out can be very different. As with all fire requirements around the world, those related to exterior facades are based on national experience with catastrophic fires as well as local building tradition.

One approach used in many countries is to apply combustibility and/or flammability requirements to each material used in the façade system—the rationale being that by controlling the performance of each component, the combined system should perform appropriately safe. The requirements are linked to the perceived hazard for the building and are dependent on the height of the building and its occupancy. A typical example is to require the use of only non-combustible materials if the building exceeds a certain height, which can range from 12 to 50 meters depending on the country.

Another approach is to require testing of the entire façade system, often in a large-scale test to replicate the perceived real behavior of the system. Some countries have chosen to include large-scale testing of façade systems in their requirements, while others have opted to use large-scale façade testing in addition to testing of individual components. Despite that these countries are all trying to mitigate the same hazard, there are almost as many tests as there are countries with testing requirements. Key differences exist in the tests, including heat exposure, testing geometry, and criteria for passing the test. Consequently, the same exterior wall system might get very different results in different tests, one deeming it safe and another unsuitable for its intended purpose. Fire, however, does not recognize geopolitical borders and behaves the same way everywhere. Yet, worldwide, our testing contains no consistent scientific basis that could help eliminate these critical safety differences from country to country.

Adding to the challenges there is a lack of understanding of how different materials interact within combustible exterior wall assemblies during fire. A minor change in the material, geometry, or assembly of a façade system can drastically impact its flammability so it is dangerous to assume that these variations can be used interchangeably in building design without further research. Yet too often these simplified assumptions are made causing the safety of the final design to be questionable. The complexities of these systems require a high level of competence of the designer.

Not only is a high level of competency required by the designer. An important aspect that is often overlooked when discussing the fire performance of exterior walls is the quality of the installation of these systems. When using combustible materials, it is critical to ensure that they are protected from ignition and that added protective measures such as fire stopping and barriers are installed correctly. A system that was designed to be safe can turn deadly if not installed correctly. Many installers are often unaware of how even minor details can have major impact on how the finished system will perform if exposed to fire. A highly skilled workforce is therefore essential if we hope to ensure the safety of these complex façade systems.

Where is the data?

So how can we improve our understanding of the fire performance of combustible exterior walls and thereby implement better codes, regulations and tests? This will require research into the fire performance of materials and systems and especially how they interact. An important part of this research is to learn from the fires that has already happened. Without that we can understand neither the true scope of the problem nor the details necessary to create consistent testing requirements and building regulations.

Unfortunately we do not have detailed data about these fires: the kind of exterior assemblies that were used, what kind of fire testing (if any) those assemblies had been subjected to, how the fires started and spread, the types of safety regulations that may have been in place, and more. Without that level of detail, we are unable to make a convincing case for jurisdictions to institute new or more stringent testing methods. Relying on media reports also means we can’t gather data on the small fires that never developed into large disasters due to fire safety provisions working as they were intended. The information we are getting is skewed towards disaster and provides few lessons about what works compared to what doesn’t.

Even data recorded by the fire service after incidents have their challenges. Researchers from different countries have indicated that incident reports often provide limited information about the type of façade system, the components used in the assembly, and the development of the fire. Another limitation of international data is that different metrics are often recorded by different countries. If data collection is inconsistent between nations, it is impossible to compare the frequency of incidents without a high level of uncertainty as well as to quantify how different requirements around the world impact the level of risk. With few exceptions, we continue to validate unknown quantities of different building materials with various test methods and often install them through an undertrained workforce bound by minimal regulations. The progression of these practices is seemingly bottlenecked by a lack of knowledge and fire incident data to validate or disprove hypotheses.

If we do not learn from fire incidents, we will continue to try to solve a set of problems we can barely identify. There is an opportunity to learn from failures, and even successes, and develop strategies based on real-world fire incidents. We owe it to the fire victims as well as future generations to do better.

A first small step towards getting more data on the façade fire problem is a new Wikipedia page [3] with a list of high-rise façade fires. The page is set up by the Hazelab research team at Imperial College with support from NFPA and everyone with knowledge of high-rise façade fires are encouraged to add information to the list. While in no way a perfect solution or a way to get all the detailed data that researchers need it is a beginning and a way to explore alternative ways to get the data we need while waiting for national fire data systems to catch up.

References

[1] M. Bonner & G. Rein; Flammability and Multi-objective Performance of Building Façades: Towards Optimum Design; International Journal of High-Rise Buildings December 2018, Vol 7, No 4, 363-374

[2] https://www.nfpa.org/-/media/Files/News-and-Research/Fire-statistics-and-reports/Building-and-life-safety/RFFireHazardsofExteriorWallAssembliesContainingCombustibleComponents.ashx

[3] https://t.co/fwNIp6cK0v

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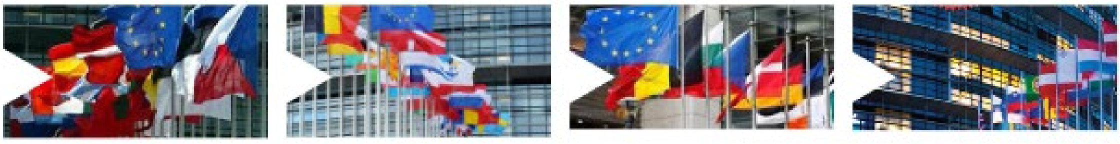

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DEVELOPING FIRE SAFETY ENGINEERING IN AFRICA – AN EDUCATIONAL SPARK IS SLOWLY BECOMING A CONTENTAL FLAME

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INTRODUCTION

As the population, mining activities, informal settlements, cities and industrial centres in Africa continue to grow at an alarming rate there is an important question to be asked: how can we keep Africa fire safe? In the developed world it can be seen that fire safety engineering (FSE) has made significant progress in protecting people, assets and the environment from the destructive effects of fire. The consultants and practitioners developing FSE solutions have often been trained through formal university programs. However, the FSE degree programmes in countries such as the USA and UK are many decades old, require extensive resources, and have highly trained staff members with rare skills. Until recently Africa had virtually no formalised university training for consulting fire safety engineers. This article gives a short introduction to fire safety educational work that has been developing on the continent in the past few years.

Structural fire engineering research at Stellenbosch University (located in the beautiful winelands outside of Cape Town, South Africa) started in 2014 with a single PhD study. Through this study and ongoing research other students and team members have gradually became involved. In 2017 the Fire Engineering Research Unit at Stellenbosch University (FireSUN) was founded, with a focus on developing technical expertise in fire safety. The team has now expanded to currently have around 20 students, including 6 PhDs, 7-9 research masters students, 2 postdoctoral fellows and 4-5 final year students working on fire safety research topics. Two formal postgraduate taught courses have been developed, namely structural fire engineering and fire dynamics. A third course on the fundamentals of fire safety engineering design is currently being developed.

However, even more exciting than the development of FSE research at one university is the fact that FSE is slowly starting to have an impact in multiple countries. In 2020 students and staff from the University of Zambia, University of Nairobi (Kenya), and Central University of

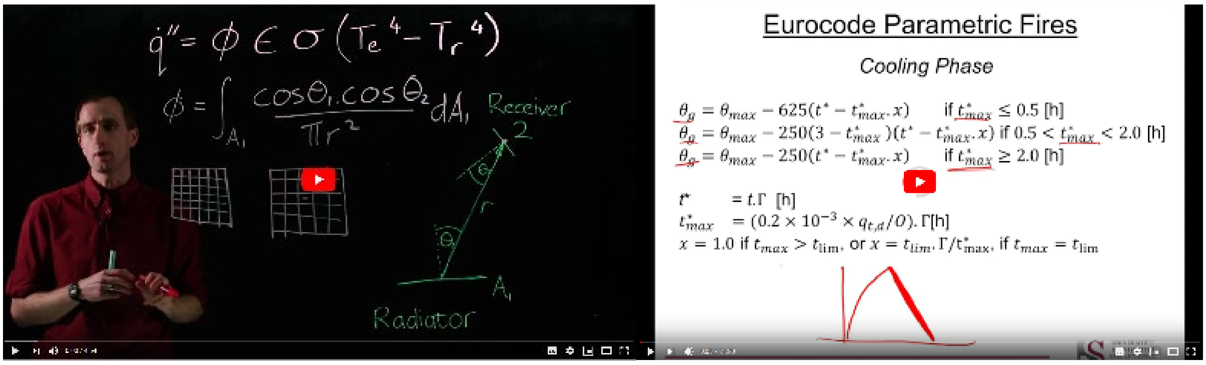
Technology (Bloemfontein, South Africa) will be attending some of the courses being developed. Furthermore, students and consultants from other countries are starting to get involved, such as in Namibia and Nigeria. The location of these groups is shown in Figure 1. All this represents a big step forward in a field that has been heavily neglected on the continent.

Figure 1: Locations of universities or individuals getting involved in developing fire safety in Africa. Hopefully the work will spread across much of the continent.

SUPPORT FOR THE WORK

Fire safety education not only requires multiple staff members but also expensive equipment and laboratories. Hence, there has been a number of interim steps in developing the capacity to undertake research, teaching and testing. A large project on informal settlement fire safety in collaboration with the University of Edinburgh, sponsored by the EPSRC (UK), helped the initial work. Additional assistance was then obtained from the Lloyd’s Register Foundation (UK) to specifically focus on the educational development of fire engineering, through assisting in sponsoring the creation of two taught postgraduate courses (structural fire engineering & fire dynamics). In 2020 a second educational grant has been received through the Engineering X program by the Royal Academy of Engineers and Lloyd's Register Foundation together. This is allowing for the creation of a third taught course on the fundamentals of fire safety engineering (to be rolled out late 2021/early 2022), and to also make the new courses 100% online, such that they can become more widely accessible. Due to the limited staff capacity available, and the large geographic distances between participants, the team has rapidly embraced online teaching and technology to promote FSE education, as shown in Figure 2. Local fire testing has been made possible through generous support by a local fire testing laboratory in Cape Town, Ignis Testing. It has been exciting that a small research team has been provided with access to standard fire test furnaces and other facilities.

The development of highly technical postgraduate courses is also not possible without technical input and assistance. To this end the University of Maryland, along with academics from other universities, have provided initial guidance on the establishment of fire dynamics courses. Prof Erica Fischer from Oregon State University visited South Africa in 2019 and helped run two structural design seminars for industry participants. The National Fire Protection Association (NFPA) has provided advisory assistance and access to material to bolster the efforts. The SFPE core competencies and degree curricula have formed the basis for guiding the development of educational content (although it will be a number of years before all aspects can be addressed).


$$\dot{q}'' = \phi \epsilon \sigma (T_e^4 - T_r^4)$$

$$\phi = \int_{A_1} \frac{\cos\theta_1 . \cos\theta_2}{\pi r^2} dA_1$$

Eurocode Parametric Fires

Cooling Phase

$\theta_g = \theta_{max} - 625(t^* - t^*_{max} . x)$ if $t^*_{max} \leq 0.5$ [h]

$\theta_g = \theta_{max} - 250(3 - t^*_{max})(t^* - t^*_{max} . x)$ if $0.5 < t^*_{max} < 2.0$ [h]

$\theta_g = \theta_{max} - 250(t^* - t^*_{max} . x)$ if $t^*_{max} \geq 2.0$ [h]

$t^* = t . \Gamma$ [h]

$t^*_{max} = (0.2 \times 10^{-3} \times q_{t,d} / O) . \Gamma$[h]

$x = 1.0$ if $t_{max} > t_{\lim}$, or $x = t_{lim} . \Gamma / t^*_{\max}$, if $t_{max} = t_{\lim}$

Figure 2: Embracing the electronic world - the development of fire engineering has rapidly gone online at Stellenbosch University. Here are YouTube explanations on the calculation of the configuration factor for radiative heat transfer and Eurocode parametric fires

WE'RE NOT ALWAYS AS FAR BEHIND AS YOU MAY THINK…

An advantage of having a young, energetic team in a country/continent with minimal academic fire engineering knowledge is that a variety of unusual projects have been started, with some of these being shown in Figure 4. This has allowed innovative research to be conducted in relatively new fields.
Some of these include:

- Informal settlement fire safety testing, modelling and development of guidelines
- Development of fire spread models for large informal settlement fires
- Development of fire safety products using 3D printed concrete
- Testing of Ecobrick walls in fire. (Ecobricks are highly popular plastic bottles that are filled with non-recyclable plastics and waste material, and then built into walls

such as for schools and crèches in developing countries. [Many a fire engineer reading this is currently worried about the combustible plastics being put into public buildings without understanding their usage.])

- Development of novel cellular steel structures through large-scale testing. The largest standard testing furnace in Africa (4x6m) was developed by Ignis Testing Laboratory (a local partner) to assist this work.
- Understanding fires on passenger trains based on the extensive number of arson attacks that have occurred in South Africa. This being done under the national passenger train agency.
- Timber structures in fire, including connection modelling.
- Analysis and benchmarking of test standards for South Africa.
- Computational modelling of large structures.
- Fire modelling
- Petrochemical facility fire safety

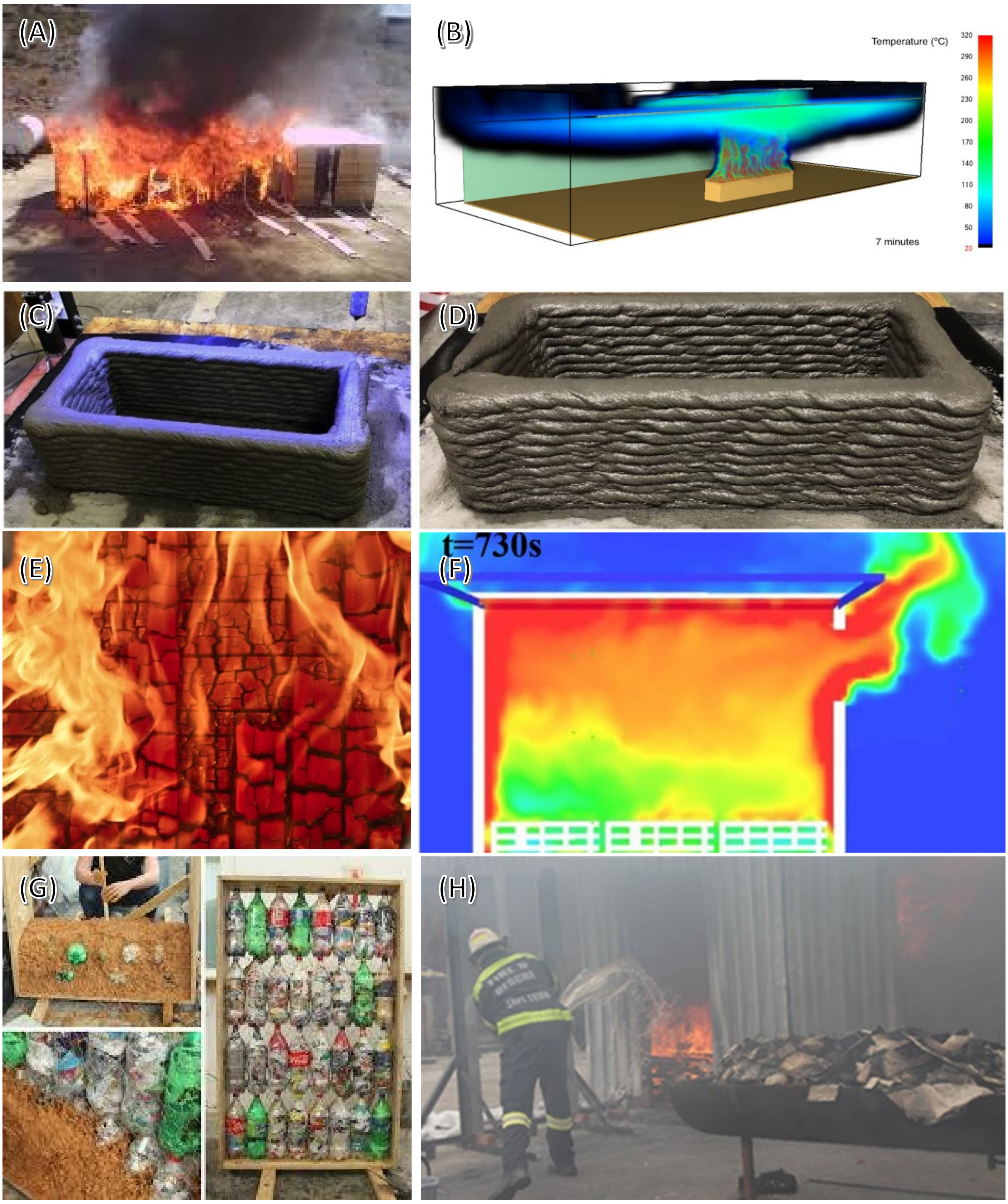


Figure 3: Examples of research or consultanting projects currently underway: (A) Large-scale testing on informal settlement dwellings, (B) model of a burning train in a manufacturing facility, (C & D) 3D printed concrete being tested for fire resistance, (E) charring of South African pine in a furnace test, (F) computational modelling of an informal settlement dwelling, (G) testing of Ecobrick walling systems, (H) benchmarking of suppression products for informal settlements (including bucket brigades and proprietary products).

CONCLUSIONS

There is a huge fire safety educational mountain to be climbed to develop a thorough fire safety engineering curriculum at multiple universities on the African continent. However, there is progress, and hopefully in the years to come Africa can start solving her own fire safety problems by producing well-trained engineers. Partnerships with leaders around the world is making all of this possible.

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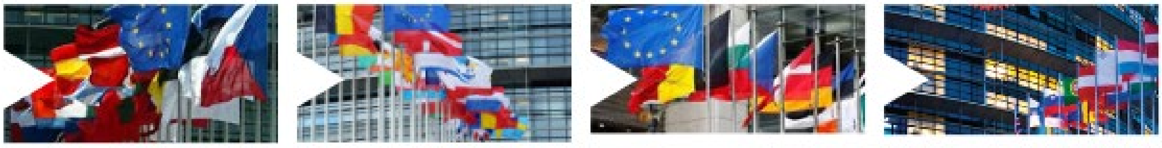

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ANTHROPOMETRIC DATA AND MOVEMENT SPEEDS

By: Matthew Foley, SLS Consulting, Inc.

This paper summaries a study completed by Gales et al. It reviews the major components of the study and includes a selection of references used within the study. Readers are referred to the full study report for more information.

Introduction

The goal of the SPFE Research Roadmap is to identify future research needs to support the profession of fire protection engineering. An item identified during the inception of this program is the urgency to update the available data related to human behavior in a fire incident.

Developing an understanding of how occupants move in a building during a fire is of key importance in fire protection engineering. However, many of the egress models evaluated today use movement speeds and anthropomorphic data from research that was conducted over 40 years ago. At the time of its collection, sophisticated modeling of human behavior was heavily constrained by the limited processing power of computers at the time. As such, only rudimentary data capable of being modeled at the time was collected. The representativeness of this data has recently been subject to scrutiny from the fire protection community. In fact, authors of a widely accepted North American dataset have openly stated that their data may no longer be applicable and requested further data is collected to reflect changes in demographics.

We are now fortunate to have access to sophisticated egress modeling software capable of modeling more complex human behavior. Despite these computational advancements, the level of uncertainty associated with input data has remained largely unchanged since the early stages of the egress modeling development and analyses. Therefore, the progression of human behavior analyses is seemingly dependent on the cultivation of new, modern datasets.

Through a collaborative effort, York University and Arup led an SFPE Foundation Study with Lund University to compile specific movement and anthropomorphic data sets. This collaboration led to the development of a human factor database to complement the SFPE Handbook. This database will be available to the fire protection community to provide more applicable datasets for use in performance-based design and egress modeling. This new design tool intends to reduce the level of uncertainty in egress modeling by providing data to better represent the unique design challenges of each specific project.

Anthropometric Data and Movement Speeds

In addition to the existing compendium of movement data within the SFPE handbook, a number of universities and researchers have collected movement data. As part of this project, this includes York University and Arup who have been collecting movement data to support consultancy projects since 2015. Rather than focus exclusively on data collected through laboratory studies, researchers began to evaluate field studies of real infrastructure, including security footage and hand recordings. The findings of this SFPE Foundation study were published in “Anthropometric Data and Movement Speeds” in May 2020.

As part of the study, the research team improved upon an automated tracking technology methodology. Most of the data in this study was collected through high-resolution video taken from carefully selected vantage points. Data was extracted from this footage using open-access software, called Kinovea, originally designed to measure kinesthetic movements during a sporting event. The software was further modified by York researchers and then applied. Part of the analysis was to create a perspective grid that recognizes occupants as they walk between markers.

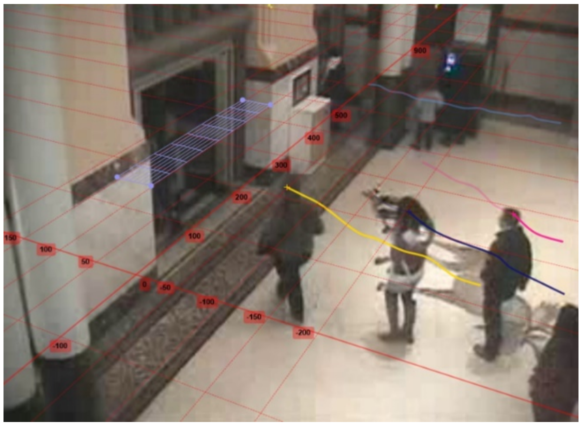

Figure 1: Movement Data Extraction Example using Automated Software

One of the more comprehensive studies in this report was completed at York University Stadium. Every summer, this stadium is host to several professional tennis tournaments. The stadium includes a pedestrian village that features restaurants, shops, and isolated events. The research team has been granted exclusive access to this stadium for research purposes since 2018.

The ethical considerations of studies involving human subjects are critical. In the York University Stadium study, each patron ticket for the tennis tournaments includes a written explanation of the study and disclosed that images of the attendees may be used for publication and research purposes. However, the university did not allow the research team to manipulate ground conditions or invoke emergency conditions of egress.

The primary areas of focus in this study included (1) general circulation, (2) movement on stairs, (3) accessibility, and (4) egress with urgency.

The study identified different age demographics in their evaluation of movement speeds for general circulation. The demographic categories included children, young adults, adults, and the elderly. In general, the occupants in this study traveled with a faster movement speed than the values typically used in egress modeling. The data also found a significant difference between demographic categories. For example, elderly occupants traveled as much as 19 percent slower than the average adult. These findings are compared with the standard Fruin Commuter Movement profiles in Table 1

		Speed (m/s)				
Agent Profile	**Sample Size**	**Min**	**Max**	**Mean**	**Median**	**SD**
Child	52	0.34	5.04	1.45	1.30	0.75
Young Adult	50	0.71	3.92	1.61	1.52	0.58
Adult	51	0.67	3.53	1.64	1.65	0.59
Elderly	50	0.40	2.52	1.32	1.23	0.48
Fruin	-	0.65	2.05	1.35	-	0.25

Table 1: Able-Bodied Profiles for Unimpeded Movement on Level Ground

The SFPE Handbook provides guidance for movement speeds in stadium stairs. This guidance is derived from a study at a German tennis tournament and reports an average speed of 0.71 meters per second. This value is comparable to the findings of the York University Stadium study, which reports an average movement speed of 0.73 meters per second. However, the York University Stadium study refined these movement speeds to identify age demographics and whether occupants were descending or ascending the stairs. The new study found that elderly people had an average movement speed of 0.52 meters per second, representing a 30 percent reduction in movement speed compared to adults. These findings are summarized in Table 2.

		Horizontal Speed (m/s)					
Agent Profile	**Sample Size**	**Min**	**Max**	**Mean**	**Median**	**SD**	**Direction**
Adult	53	0.36	1.26	0.71	0.70	0.18	Descent
	54	0.42	1.40	0.77	0.72	0.20	Ascent
Elderly	50	0.16	0.96	0.50	0.52	0.18	Descent
	51	0.16	1.14	0.55	0.55	0.15	Ascent

Table 2: Able-Bodied Profiles for Unimpeded Stair Movement

Movement profiles were also created for occupants with accessibility needs, including disabilities and other mobility limitations. Although this demographic only represented 3.7 percent of the total occupants, a sample size of 2,430 mobility profiles have been collected since 2018. Overall, the average movement speed of people with accessibility needs was 33 percent slower than those without accessibility needs. These findings are summarized in Table 3.

		Speed (m/s)				
Agent Profile	**Sample Size**	**Min**	**Max**	**Mean**	**Median**	**SD**
Cane	62	0.21	1.68	0.91	0.88	0.28
Crutches	5	0.35	1.22	0.68	0.66	0.34
Mobility Scooter	23	0.57	2.71	1.39	1.47	0.45
Person Req. Assist	61	0.16	2.02	0.98	0.95	0.41
Walker (Rollator)	15	0.21	2.02	1.07	0.98	0.59
Walking Stick	23	0.14	1.68	1.01	1.04	0.41
Wheelchair (Electric)	17	0.06	1.76	1.08	1.01	0.46
Wheelchair (Manual)	54	0.06	3.54	1.17	1.10	0.50
Total	260	0.06	3.54	1.05	1.02	0.44

Table 3: Mobility-Limiting Impairment Profiles for Unimpeded Movement on Level Ground

As previously mentioned, the university prohibited the use of a simulated fire scenario to evaluate movement speeds during an emergency. In lieu of an emergency, researchers sought to collect movement speeds in a situation that may be considered high urgency. A rare data collection opportunity presented itself when a torrential downpour of rain began during a filming event. Researchers filmed the egress of nearly 2,000 people during the stadium evacuation. The footage identified areas of crowd congestion, observed the decision making of occupants, and recorded a total egress time of 2.5 minutes with an average travel distance of 43 meters. Whilst a fire scenario would be localized and only likely affect those in the immediate vicinity, the event may be considered more akin to a terrorist event or a bomb threat.

In addition to the York University Stadium study, “Anthropometric Data and Movement Speeds” includes movement profiles for occupants in inter-city railway stations, museums, and retirement homes. Pending peer-review, the data recorded in these studies will eventually be featured in the new SFPE Database and made available to the fire protection engineering community for use in egress modeling.

Determining Evacuation Capability with Biomechanical Data

Current design guides typically use a basic flow rate for a single uniform population, which has not changed since the regulation of door and passageway sizes in the mid-20th century. The loss of confidence in the current data is due to a recognition of the ever-increasing proportions of elderly, obese and mobility impaired in society. These proportions have increased significantly since the original observations were made of the egress and circulation ‘flows’ of office workers and commuters between the 1950s and the 1980s. Despite the recognition of the potential dangers of using the original datasets, there has been no fundamental research carried out to study the effect of changing population demographics, or the nature and causes of the observed flow behaviours and associated parameters. Demographic changes have now provided the impetus and have reinforced the need to consider a “first-principles” approach to understand pedestrian movement in populated spaces.

In order to avoid increasing design and life safety implications, a fundamental change needs to be made to the pre-established approach to modelling occupant movement in populated spaces as uniform flows. As part of the SFPE Foundation study, York University sub-contracted Lund University to explore anthropometric datasets that can be used in future data collection methodologies. Rather than collect data about human movement through traditional experiments, “Determining Evacuation Capability with Biomechanical Data” focuses on the development of a biomechanical model linked to the characteristics of each individual. This new model is intended to enable the movement of a single file crowd to be derived from these demographics and biomechanical characteristics of the people in it.

The model focuses on the unimpeded normal walking speed of an occupant and its reduction due to the persons' intention to avoid collisions with other occupants around them. Additional biomechanical variables considered in this study include:

- Demographics parameters: including preferred walking speed, height, foot length, and body sway
- Gait Parameters: Factors including step length and step extent
- Contact Buffer: The distance between potential points of contact between the individual and the occupant in front of them
- Movement Adaption Time: The time needed for an occupant to recognize a change in movement conditions and adjust their walking speed as needed

Some of these basic principles are illustrated in Figure 3.

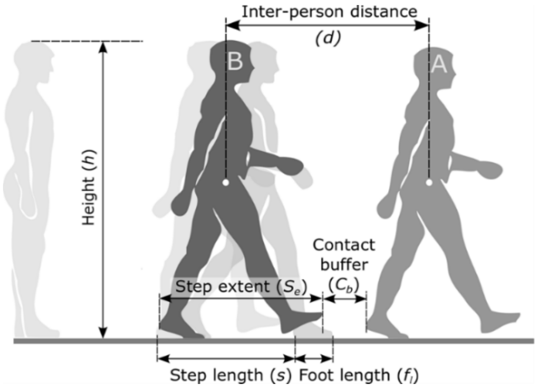

Figure 3: Components of Pedestrian Movement in a Congested Space

Basically, the model consists of the preferred speed of a person and their intention to avoid collisions with other pedestrians based on their physical and cognitive abilities. It can currently be used to predict walking speeds and single file flow and is based on the equations, presented in the report, in a spread sheet program. The “contact buffer” is the manifestation of the individual’s desire to avoid colliding with the person in front, where a person leaves enough space to allow for a potential sudden stop or change in walking speed of the person in front. This “contact buffer” also has a minimum value representing a comfortable “queue spacing” between individuals. In the project, some of the variables were quantified based on observations from a set of experiments.

All subjects in the experiments in the study were young, healthy students of Lund University. However, the results of this study were compared to available experimental data. Data produced by Cao (Cao et. al, 2016) was used for the elderly and young adults, while data produced by Wang (Wang et. al, 2018) was used for children. The results of this predictive model and the experimental data are compared in Table 4.

Parameters & calculated predictions	Lund Students	Elderly	Young	Children
Height (m)	1.80	1.62	1.64	1.42
Preferred Unimpeded Walking Speed (m/s)	1.29	0.95	1.23	1.29
Max Density (p/m)	3.28	2.58	3.40	4.34
Adaption Time (s)	0.37	0.68	0.37	0.37
Foot Length (m)	0.29	0.28	0.28	0.22
Step Extent Factor (at vu)	0.92	0.92	0.92	0.92
Peak Single-File Flow [p/s]	1.03	0.71	1.06	1.23
Percentage of Lund students flow rate	100%	69%	103%	119%
Difference from Lund students flow rate	0%	-31%	-3%	19%

Table 4: Summary of Predictions from the Movement Adaption Model Based on Parameters from Cao (2016) and Wang (2018)

While this study provides valuable data related to the movement speed of young adults, it also provides a framework to relate demographics and biomechanical information to movement speed. In the study, the results are basically considering single file movement and the model needs to be complemented with data from larger crowds. This initial step of deriving a predictive model for single-file flow analysis from the base principles of demographics, biomechanics and contact-avoidance shows remarkably good alignment with other overall published data on pedestrian movement. The mathematical model can potentially be used by fire protection engineers to derive suitable flow rates from the anticipated demographics of the population of the building. Further work will study flows across multiple lanes, using the same principles in order to build up a set of predictive calculations for a wider set of scenarios in different buildings with different occupancies (mixed ability, different elderly demographics, schoolchildren etc.).

SFPE Database

This SFPE Foundation study represents an important step in the development of a searchable database for the occupant characteristics used in egress models. While this searchable database will eventually be populated with data from new research, this database will initially be configured with the existing datasets found in the fifth edition of the SFPE Handbook.

The transition of the database and legal framework is still underway. It is anticipated that future research, through a collaboration with York University and SFPE Conseil St-Laurent, Québec will focus on buildings with limited availability of data, including airport and railway data. Additionally, a comprehensive validation exercise is being developed to support the introduction of these datasets into egress models.

Conclusion

A majority of the data related to human behavior in fire events is based on research completed over 40 years ago. As a result, many of the egress models completed today are evaluated with occupant movement speeds that were intentionally limited to facilitate limited computing power. New technologies, including developments in artificial intelligence and automated tracking software, are capable of recording new datasets that are more representative of changing demographics. As these datasets become increasingly available, the SFPE Digital Database will serve as a means for the fire protection community to share data in a standardized format and continue to evolve the practice of egress modeling. In addition, the data collected in future studies will also consider demographical and biomechanical data in order to base models on a first principle approach, this to consider anticipated changes in the population characteristics.

Download the Full Report

https://cdn.ymaws.com/www.sfpe.org/resource/resmgr/foundation/research/gales_report.pdf

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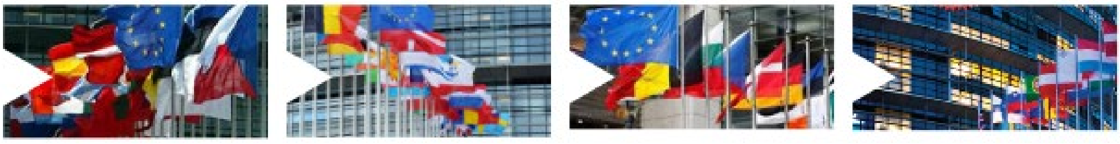

Q3 2020 ISSUE 19 AN OFFICIAL PUBLICATION OF SFPE

THE ROLE OF SFPE IN REDUCING BARRIERS TO THE EFFECTIVE IMPLEMENTATION OF PERFORMANCE-BASED DESIGN

By: Greg Baker, Fire Research Group Limited, New Zealand

Introduction

This article is the third in a series of articles that summarise a presentation entitled *The Contribution of the RTM to the Global Advancement of Performance-Based Design*, given by the author at the SFPE 2020 Performance-Based Conference & Expo, which was staged in Auckland, New Zealand from 11 to 13 March 2020.

This third article deals with the primary theme of the conference presentation, namely the broader role of the SFPE as a whole, and the SFPE's *Standing Committee for Research, Tools and Methods* (the so-called 'RTM'), in advancing the implementation of performance-based design (PBD) internationally.

As with the previous articles in the series, the context for this third article is a new SFPE committee which has recently been formed to develop a new SFPE Standard on PBD. One of the objectives of this new standard making committee is to reduce the barriers to the effective implementation of PBD by producing an ANSI-accredited SFPE Standard on PBD that can be widely used and relied upon around the world in numerous regulatory jurisdictions.

The first article in this series was entitled *Defining Performance-Based Design* and was published in the Q1 2020 Issue 17 edition of SFPE Europe Magazine [1]. The article provided the author's definition for PBD and the comparative status of different exemplar New Zealand Building Code compliance documents in relation to the definition.

For clarity, it should be noted that the views expressed in this and previous articles (and the conference presentation) are those of the author alone and do not represent the formal view of the above-mentioned committee, or for that matter the SFPE as a whole.

The SFPE Standing Committee for Research, Tools and Methods (RTM)

The RTM is one of six standing committees within the SFPE's organizational structure, the other five standing committees being: (1) Continuing Professional Development (CPD); (2) Membership and Chapter Relations (CMC); (3) Outreach and Advocacy (COA); (4) Professional Qualifications (CPQ) and (5) Nominations Committee.

As noted on the Standing Committees page on the SFPE website [2], "the work of the Society is largely done by six standing committees and their respective subcommittees" with each standing committee led by a chair (or co-chairs) and members of the committees being primarily volunteers from the Society's membership base, although it is important to note that non-members of SFPE can and do contribute to the work of the committees.

The RTM has three key areas of activity within its scope of work [3], namely:

1. To identify, develop and oversee some of the Society's technical products and research work
2. Review new innovations emerging in the fire engineering sector, and
3. Help establish a research agenda for the international fire safety engineering profession.

The SFPE currently has seven discrete technical products, as follows:

1. Fire Protection Engineering (FPE) Magazine
2. FPE Extra Digital Magazine
3. SFPE Europe Magazine
4. Fire Technology
5. SFPE Handbook
6. SFPE Engineering Guides, and
7. SFPE Standards (ANSI-accredited).

Th RTM is responsible for the technical products items 5, 6 and 7 in the above listing.

There are four separate subcommittees within the RTM operational structure:

1. The Subcommittee for Handbook Development (SCHD) – SCHD is responsible for the SFPE Handbook
2. The Subcommittee for Research and Innovation (SCRI) – SCRI is responsible for identifying and reviewing emerging innovation trends and the research agenda
3. The Subcommittee for Codes and Standards Liaison (SCCSL) – SCCSL is responsible for the citation of SFPE technical products in codes and standards that are published by external organisations such as the National Fire Protection Association (NFPA) and the International Code Council (ICC), and
4. The Subcommittee for Standards Oversight (SCSO) – SCSO oversees and is responsible for the technical products (SFPE Standards and SFPE Guides) that the RTM produces for the Society.

Within the current RTM/SCSO work programme, there are eight active projects in progress – four Standard making committees and four Guide task groups – including the aforementioned PBD Standard making committee.

Barriers to the Effective Implementation of PBD and Key Needs to Reduce Barriers

The second article in this series was entitled *Barriers to the Effective Implementation of Performance-Based Design* and was published in the Q2 2020 Issue 18 edition of SFPE Europe Magazine [4]. The article gave details of seven discrete barriers, as follows:

Barrier 1 - Legal/Regulatory

Barrier 2 – Definitional Clarity

Barrier 3 - Sector Capability

Barrier 4 - Quantification

Barrier 5 - Probabilistic Acceptance Criteria

Barrier 6 - Accepted Tools and Methods

Barrier 7 - Societal Impact Barrier

The same article also provided some specific examples of these barriers.

The article concluded by distilling the seven barriers down into three key needs that, if addressed appropriately, would reduce barriers to the implementation of PBD. The three key needs were:

Key Need 1 – International Acceptance

The first key need is for comprehensive design methodologies to be developed by authoritative organisations that have the international mandate to do so. This is as an important first step to ensure such design methodologies have sufficient credibility to achieve widespread international acceptance.

Key Need 2 – Quantified Design Criteria

On the basis of the definition presented for PBD, the second key need is for performance and acceptance criteria to be quantified with the combination of specific target values and an acceptable probability of non-exceedance for each target value.

Key Need 3 - Tools

The third key need is for suitable computer tools to be developed, validated, introduced and supported so that practitioners are able to consistently implement probabilistic design criteria in their design analyses.

Role of SFPE to Reduce Barriers

What role does the SFPE and the RTM have in reducing the barriers to the implementation of PBD in a global context? As the very name of the RTM suggests (Research, Tools and Methods), the committee has an important and influential role to play in the global fire safety engineering community and the building regulatory sectors to reduce barriers to the effective implementation of PBD. At the same time, the wider SFPE has an equally important contribution to make in parallel to the efforts of the RTM. As the professional society representing those practicing in the field of fire engineering internationally, the SFPE has the credibility and profile to advocate at an international, regional, national and local level.

Reducing Barrier 1 - Legal/Regulatory

In relation to legal and regulatory barriers, for jurisdictions where the existing Building Code is either not performance-based, or there are no provisions within the existing Code to permit PBD, the wider SFPE has a very important and crucial advocacy role to continue to promote and advocate for the adoption and implementation of PBD.

Reducing Barrier 2 – Definitional Clarity

With regard to the barrier of a lack of definitional clarity as to what constitutes PBD, the RTM has an important role to play by increasing the visibility of what the term PBD actually means by firstly developing a very clear and widely-applicable definition itself, and then by promoting the definition as widely as possible in the international fire engineering community.

Reducing Barrier 3 - Sector Capability

For the third barrier where a lack of sector capability inhibits the effective implementation of PBD, the existing and widespread educational and credentialing initiatives within the Society will continue to be pivotal on behalf of the fire engineering community to improve the capability of the sector at the global level.

Reducing Barrier 4 - Quantification

In jurisdictions where a lack of quantification of building code clauses (in particular at the functional, i.e., the most detailed level) is in effect hindering the implementation of PBD, once again the RTM has an instrumental role to play by actually supporting the development of the numerical metrics that are needed by the code writers to include in building code provisions. The wider SFPE also has an important support role to encourage and enable the necessary technology transfer to occur from the RTM outputs to external code-writing organisations.

Reducing Barrier 5 - Probabilistic Acceptance Criteria

On the definitional premise that PBD involves probabilistic methods, for PDB to be implemented, the building code clauses that contain acceptance criteria (sometimes known as ‘performance criteria’) most include targets that are stated in probabilistic terms. In a similar vein to Barrier 4, the RTM can make an important contribution by establishing what are acceptable probabilistic thresholds, based on consensus from a wide international group of stakeholders and practitioners. Again, the Society has a support and promotional role to increase the scale and breadth of uptake internationally.

Reducing Barrier 6 - Accepted Tools and Methods

The mandate of the RTM is to develop tools and methods that are technically robust and fit for purpose for the international fire engineering community. Delivering upon this mandate will prove to be a very effective ways that the work of the RTM and the SFPE can help to reduce the barrier posed by a lack of suitable design tools and methodologies. The credibility that the SFPE brand brings to such tools and methods can also not be underestimated and such SFPE endorsements do not need to be limited to products that are produced by the Society.

Reducing Barrier 7 - Societal Impact Barrier

The most difficult barrier for the RTM and/or SFPE to help reduce is that posed by the awareness that PBD practice brings to the question of accepting a certain (albeit very low) level of fatalities and injuries in fire where the design has followed a PBD process. That being said, the Society must continue to support and contribute to the wider discussion about the benefits and advantages of PBD.

Summary - Key Messages

The RTM is one of six standing committees within the SFPE organizational structure. One of the key activities of the RTM is to produce Engineering Guides and Standards, and the SFPE Handbook, which collectively constitute some of the most important technical publications that are used in the international fire engineering community.

A number of significant barriers to the implementation of PBD exist internationally, including legal/regulatory barriers, the capability of the sector, quantification of code clauses, and accepted design tools and suitable engineering methods.

These barriers can be consolidated into three key aspects, namely international acceptance, quantified design criteria, and tools.

The SFPE and RTM continue to have a vitally important role to play in reducing the barriers to PBD design being implemented effectively.

A future article is planned which will provide examples of some of the tools that are available to support robust PBD practice.

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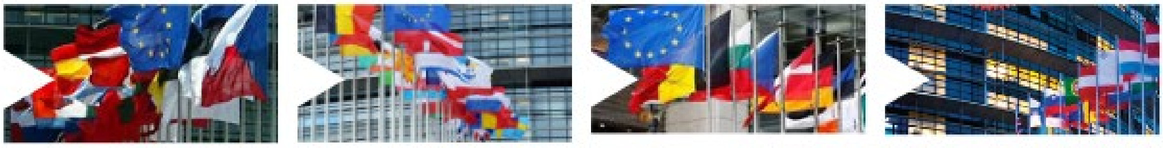

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MODERN VEHICLE AND PARKING GARAGES: DESIGN TRENDS PRESENT NEW CHALLENGES

Authored by: Victoria Hutchison, Fire Protection Research Foundation, USA
Haavard Boehmer, PE, Combustion Science & Engineering, USA

Introduction

The world's urban population has risen six-fold since 1950, with over half of the world's population – approximately 4.2 billion people – living in cities worldwide [1]. As the world undergoes a historic urban growth, ensuring city's infrastructure keeps pace with the respective population density is critical.

In highly urbanized, developed regions of the world, a lifestyle of mobility is a priority. With mobility, comes the need and desire for vehicles, as evidenced by the nearly 2 billion vehicles registered throughout the world [2]. And this volume of vehicles drives the need for parking solutions. While parking garages are abundant in practically every city on the planet, urbanization is prompting changes to vehicle parking to optimize the quantity that can be parked within a given footprint. As developers look for parking solutions in areas where land is immensely valuable, the area afforded to each vehicle is reduced, and stackable garage configurations are gaining popularity as automation and mechanization become more advanced and affordable.

But parking garages are not the only thing that has changed; vehicles have undergone a substantial transformation in their design over the last few decades as well. Government efficiency standards, in the US, Europe and China, are influencing the trends in modern vehicle design. According to the National Highway Traffic Safety Administration's (NHTSA) Corporate Average Fuel Economy (CAFÉ) standards, passenger vehicles are expected to average 54.5 miles per gallon (4.3 L/100 km) by 2025 in the US [3]. European standards have set a target of 37.5% reduction in CO_2 emissions between 2021 and 2030 [4]. These global efficiency goals have pushed automotive manufacturers to increase use of plastics and other synthetic materials to produce lighter and more fuel-efficient vehicles. Likewise, environmental goals have led to increased use of alternative fuel vehicles, such as battery electric, hydrogen fuel cells, liquified natural gas (LNG), and other emerging technologies. With so many changes to materials and fuel sources used in the design of vehicles today, it has been confidently hypothesized that modern vehicles will behave differently in a fire.

Vehicle fires developing into large, out of control events in parking structures have historically been rare [5]. But the catastrophic King's Dock Car Park fire in Liverpool, England in 2017 caught everyone's attention in the fire safety community. A 4,930 m^2 (53,000 ft^2), open-air, concrete parking garage was decimated by a fire starting in a single vehicle, which spread to over 1,150 vehicles across eight-stories [6]. The fire brigade was overwhelmed in every sense. Incidents like this have raised questions among the engineering and regulatory communities regarding whether the protection guidance for parking structures has kept pace with the evolution of the vehicle hazards and parking structure designs. While the benefits of fuel-efficient vehicles and spatially optimized parking structures are clear, researchers and code developers remain concerned about what such densely packed arrangements of modern vehicles may mean for fire protection.

To address these concerns the Fire Protection Research Foundation, in collaboration with SFPE Foundation, initiated a research project in 2019 to assess the "Impact of Modern Vehicle Hazards on Parking Structures and Vehicle Carriers" [7]. With the intent to inform fire protection schemes and design parameters for parking structures, this recently released study, led by Combustion Science and Engineering, details an analysis of the fire hazards posed by modern vehicles, the effect of changes in vehicle and parking garage design, and the factors that most significantly impact fire development and spread.

Current Protection Requirements

Vehicle parking structures are largely regulated by NFPA 88A, *Standard for Parking Structures [8],* the International Building Code (IBC) [9], or region-specific regulations such as Eurocodes, among others. NFPA 88A and the IBC are aligned on many of the regulations regarding parking structures, such as:

- Open parking structures are defined as those with greater than 20% of the exterior wall area open to the outside, with the openings evenly distributed across the wall area.
- Both standards require sprinklers in enclosed garages if they are underground or over 15 m (50 ft) high. NFPA 88A also requires automated type parking garages, such as stacker systems, to be sprinklered.
- Sprinklers and detection systems are typically not required in open parking garages if they are constructed of non-combustible or limited-combustible materials. The 2021 edition of the IBC will require sprinklers in open garages greater than 48,000 ft^2 (4,459 m^2) or 55 ft (16.8 m) in height. Most national codes within the EU require sprinkler protection in open garages above a certain floor area, height or when located below a hotel or assembly occupancy.

While these standards are regularly updated, the fire protection criteria for open parking structures has seen minimal change over the years. Modern vehicles have evolved greatly since these regulations were originally established, yet garages are still being designed based on data from 50+ year old vehicles. While vehicle-to-vehicle fire spread had a low probability in the 1960's, this is no longer true today.

Assessment of Modern Vehicle Fire Hazards in Parking Structures

With the pace of technological innovation and material advancement in our society, the evolution of vehicle fire hazards is not surprising. To make vehicles more affordable, safer, lighter and more fuel efficient, parts that were historically metal, cast-iron or aluminum, are now made of plastics or fiberglass. Everything from bumpers to gas tanks to the intake manifold in the engine are now made of plastics, and these trends are expected to continue. On the interior of the vehicle, many combustible and synthetic materials are used, and the increase in electronics presents additional fuel and ignition sources.

Developers and designers predict construction trends to go towards larger garages and increasing integration into other occupancies. Parking density will continue to increase as automation, mechanization and car stacking systems are normalized. Beyond construction changes, many garages are also integrating electric charging stations and photovoltaic systems into their designs – presenting additional hazards. So, what does this mean for the fire hazard of modern vehicles in parking garages?

Modern versus legacy vehicles and changing materials

The peak heat release rates (HRR) of modern vehicles were found to not be significantly higher than legacy vehicles. However, it was found to be highly dependent on the test conditions such as the vehicle size, the type and placement of the ignition source, ventilation conditions and the configuration of the vehicle and its surroundings, as HRR above 7 MW were found in vehicle fire tests from every decade since 1970.

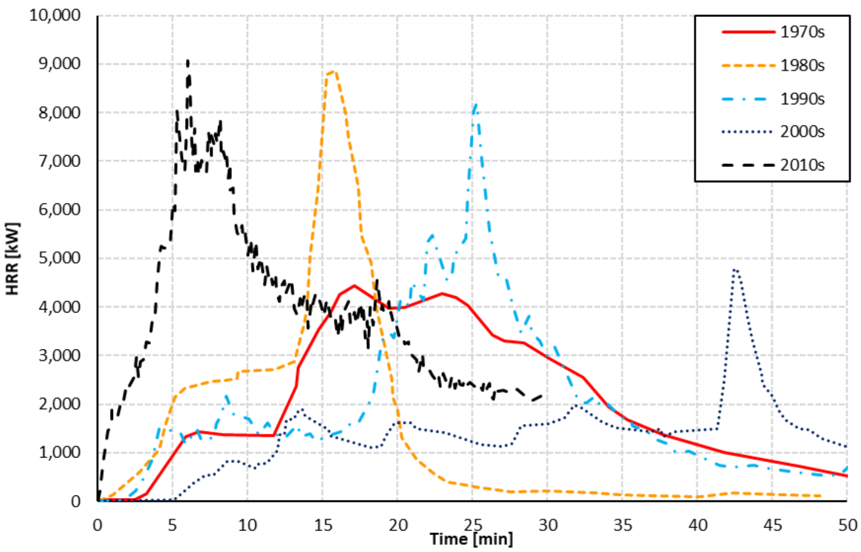

Figure 1. Vehicle HRR curves from various decades (Boehmer, Klassen, & Olenick, 2020)[7]

Vehicles more than 15-20 years old show a significant difference in average curb weight and plastic content, when compared to modern vehicles. The average US vehicle in 2018 contained 91% more plastic by weight than the average vehicle in 1970. Using the average heat of combustions of the plastics used, this yields an equivalent increase in potential chemical energy in a fire of approximately 2,300 MJ. While the fire intensity and total energy released from vehicle fires of varied ages has remained relatively constant, the changes in construction materials have reduced the time to ignition, increased the probability of spread, and altered the behavior of fire development.

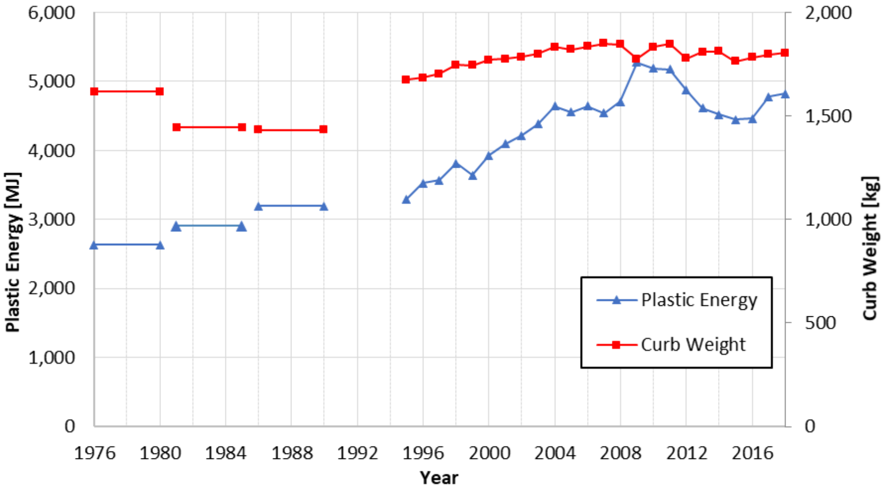

Figure 2. Vehicle curb weight and plastic content potential fire energy (Boehmer, Klassen, & Olenick, 2020)[7]

Fire Spread

Historical data has shown that a fire spreading to multiple vehicles was rare. Between 1995 and 1997, 98% of parking structure fires involved less than four vehicles, and none involved more than seven. By contrast, 14% of parking structure fires involved more than five vehicles in 2014 [10]. Past regulations assumed that fire spread from one vehicle to another would not occur, and if it did the fire department would arrive in time to control it [6]. However, the densely packed fuel loads in parking garages heightens the risk of fire spread among modern vehicles due to material changes, increase in vehicles dimensions, and tighter parking arrangements. Although limited, available test data has shown rapid fire spread between vehicles in a parking garage configuration, on the order of 10-20 minutes. Once two or more cars are involved, the time to ignition of additional vehicles is dramatically reduced (less than 5 minutes) [7].

Another concern is that plastic fuel tanks can begin to show signs of failure after a 2-5-minute pool fire exposure, which can result in a flowing liquid fire that exacerbates fire spread. As more vehicles become involved, the prolonged high-temperature exposures on the load-bearing structural elements can threaten the integrity of the structure. At the Liverpool incident, the constant high temperature exposures caused significant spalling of the concrete, which typically occurs when the internal temperature exceeds 374°C (705°F). This created large penetrations in the floor which contributed to vertical fire spread. The ceiling level temperatures experienced from an inferno of modern vehicles can also cause failure of structural steel. Once it exceeds its critical threshold of 538°C (1000°F) the load bearing capacity is reduced to half and may compromise the structure. As seen in the Stavanger Airport fire in Norway (2020), these conditions can lead to structural collapse of a multi-story parking structure.

The trends in contemporary parking solutions combined with the evolving hazard of modern vehicles has the potential to create the perfect storm for catastrophe if the appropriate protection measures are not in place.

Recommendations for Future Research

From this analysis, the following areas were identified as needing additional research:

- The factors contributing to a higher probability of vehicle-to-vehicle fire spread.
- Clarity on the “open-parking structure” definition. The location of the opening can have a significant impact on the development of the fire and the hot gas layer. Testing and modeling are needed to evaluate different opening configurations, placements and open percentages to assess its impact on fire behavior.
- Further assessment on the effectiveness of sprinkler protection on modern vehicle fires in normal parking configurations as well as car stackers.
- Impact of wind on sprinkler activation in open garage configurations.
- Impact of vehicle fires on concrete spalling.

Conclusions

Based on a review of historical fires and laboratory testing, this analysis of modern vehicle fire hazards in parking structures found that where active protection systems are required, such as in enclosed garages, incipient or fully developed vehicle fires can generally be controlled until the fire department arrives. However, where active protection systems are not required, such as in open parking garages, vehicle fires have a greater probability of developing into large or catastrophic fires due to the increased fire spread rate of modern vehicles. The trends in both vehicle and parking structure designs could lead to more devastating fires, increased property losses, business disruption and adverse environmental impacts if protection schemes do not keep pace with the evolving hazards.

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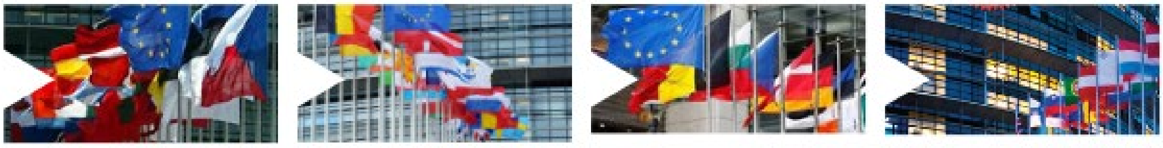

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MULTI-ZONE MODELS – BRIDGING THE GAP BETWEEN TWO-ZONE MODELS AND CFD MODELS

By: Nils Johansson, Lund University, Sweden.

There is a range of different models available for fire safety engineering, and the different models have different areas of application. When performing traditional calculations with the purpose to analyze times to untenable conditions or heat exposure to structural members the available models can roughly be grouped into three categories: hand-calculation methods; zone models; and CFD models.

Examples of hand-calculation methods are the Yamana-Tanaka methods for smoke filling, or the MQH- and Eurocode methods for calculating gas temperatures in pre- and post-flashover compartment fires, respectively. Zone models normally refer to numerical computer programs like CFAST and that is also the distinction used here. However, several hand-calculations methods also utilize, in a sense, the zone model approach by assuming that the hot gas layer holds a uniform temperature. In CFD models the domain is divide into several smaller control volumes, and the Navier-Stokes equations are solved numerically for each one of these. A typical control volume in the well-known CFD model, the Fire Dynamics Simulator (FDS) is in the order of 0.1x0.1x0.1 m^3

The step from two-zone models to CFD models is in many ways large, and sometimes maybe a bit too large when it comes to practical engineering situations. Traditional two-zone models, like CFAST, often perform well in validations studies as long as the studied situations are strongly stratified, and the hot gas layer can be assumed to be uniform in regard to temperature and composition. This normally limits the use of two-zone models to fire scenarios in small- and medium-sized spaces, like rooms in residential buildings. Consequently, the usefulness of two-zone models for fire safety engineers is limited, because engineering calculations are most often only conducted in larger commercial or industrial buildings where the prescriptive building regulations cannot be fulfilled.

CFD models, on the other hand, allows for retrieving the distribution of temperature and species concentrations in large spaces, which means that the model does not hold the same limitations in regard to compartment sizes as two-zone models. However, the computational time and complexity of the models are much greater than in zone models. This can result in that the engineer needs limit the number of calculations performed, and special training is normally needed in order to understand the model, correctly setting up the input file, and to interpret the results.

Altogether, one can perceive that there is an obvious gap in modelling capability between two-zone models and CFD models. That is the capability to perform analysis of large spaces, where prescriptive solutions might be problematic, in a short time with a model that is not more advanced than a two-zone model. This gap led to the incentive to develop a multi-zone fire model.

The multi-zone concepts

The multi-zone concept is based on the conservation of mass and energy to calculate hot gas temperatures, and the Bernoulli equation to calculate flows between the different zones. In contrast to two-zone models, where each enclosure consists of two zones, the domain is divided into several regions (horizontal) and layers (vertical) in the multi-zone concept. This makes it possible to get some estimate of the distribution of properties, like temperature, in a large space in just a couple of minutes.

The fire is specified as a heat release rate, the heat and hot gases rise upwards from the fire in a plume that enters the highest located layer in the fire region. Air and hot gases are entrained in the plume from the layers that it passes through. Mass is transported horizontally to layers in adjacent regions due to hydrostatic pressure differences. There is also a flow of mass vertically between layers in each region, which is calculated based on the conservation of mass and energy. Heat is transferred to solid obstructions through convection and radiation. 1-D conduction is used in solids. Heat is transferred between zones through the flow of hot gases and radiation. The underlying principles of the multi-zone concept have been presented in previous publications [1][2] and the reader is referred to them for a deeper explanation of the concept.

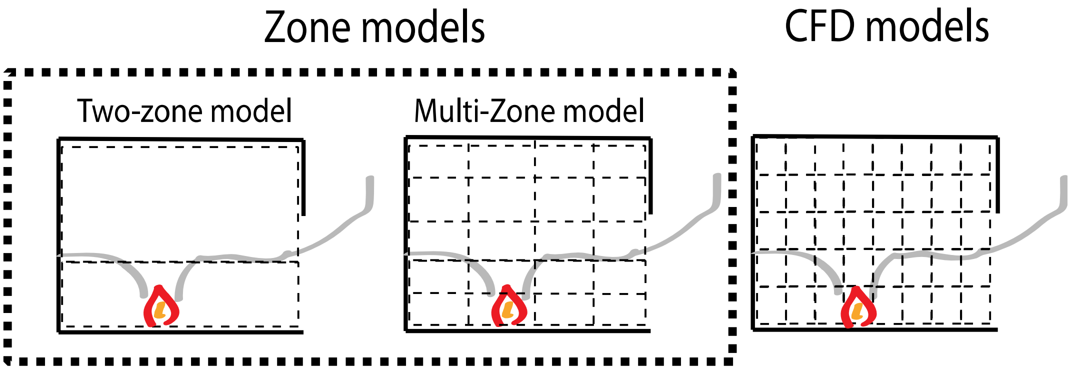

Figure 1: Principles of the different types of models.

The multi-zone concept is not as established as two-zone models since only a few models have been presented (see e.g. [1][3][4]). This means that the accuracy and possible benefits of models using the multi-zone concept is rather unknown. However, in a recent paper [5] the multi-zone concept and its usefulness in fire safety engineering, when prescriptive fire safety requirements can be hard to fulfil, have been evaluated.

The evaluation study

The evaluation of the multi-zone concept is performed by comparing data from a multi-zone model, called the Multi-zone (MZ) fire model [6], to previously published experimental data and data from simulations with FDS. The MZ fire model is freely available for download and testing at http://mzfiremodel.com.

One problem when doing this type of evaluation study is to find relevant existing experimental data, where the experimental conditions are described in such detail that it is possible to represent the experimental situation in the model. There are little data from fire experiments in large spaces available in the literature, and when it exists, the description of the experimental conditions is often inadequate to be able to use the data reliably. However, there are some examples of experimental data that were considered useful for the evaluation study. Data from three different experimental setups were used by Johansson [5].

The first set of data originates from Test#3 in the International Fire Model Benchmarking and Validation Exercise #3, BE#3, [7]. The experimental series was conducted in an enclosure that was designed to represent a room in a nuclear power plant and it measured 21.7×7×3.8 m^3. The fire was placed in the center of the room and there was a 2.0×2.0 m^2 door on one of the short ends. A heptane pool fire of just over 1 MW was used as fire source in the test.

The second set of data comes from the Murcia Atrium Fire Tests were conducted in a 19.5×19.5×20 m^3 open space [8]. The enclosure boundaries were made of steel plate and the experimental series consisted of different setups in regard to fire size and ventilation conditions. The test data used in this in the evaluation originates from a Test#3 where the exhaust fans were shut off and only used for natural ventilation. The fire source used was a fuel pan with heptane and an estimated maximum heat release rate of 2.34 MW.

The third and final data set originated from the PolyU/USTC Atrium used to study smoke filling [9]. The facility consisted of a single room constructed of concrete that measured 22.4×11.9×27 m^3. The average heat release rate, from the diesel pool used, was estimated to be 1.6 MW.

The experimental data were collected by Johansson [5], and the scenarios was modelled with the MZ fire model and FDS version 6.7.1. A visual and quantitative comparison, with functional analysis, of the correspondence between the modelling results, and the modelling and experimental results were conducted.

Result of evaluation

Results from the simulations of test 3 in BE#3 is presented in Figure 2. The results from FDS and the MZ fire model corresponds well, whilst the experimental data indicates a more rapid temperature increase during the first 100 s, especially at higher elevation ($z = 3.5$ m).

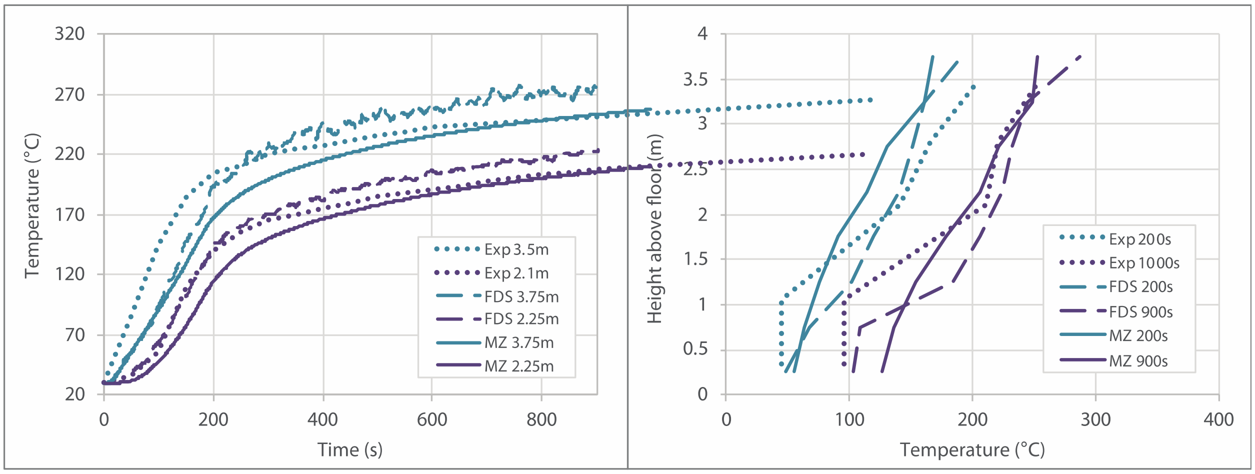

Figure 2: Temperature development (left) and vertical temperature profile at two time points (right) in the BE#3 scenario.

Results from the simulations of the Murcia fire test are presented in Figure 3. The results from FDS and the MZ fire model simulations are rather similar. The temperature in the lower part of the enclosure (see left part of Figure 3) is however predicted to be higher with FDS than with the MZ fire model. Both models give lower temperatures at higher elevation (z = 18 m) than the experimental data.

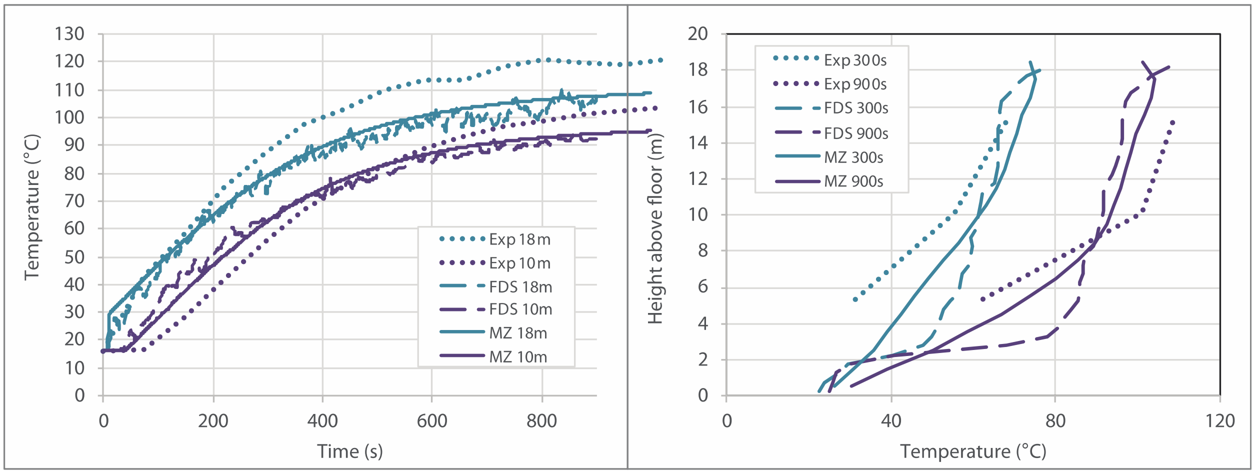

Figure 3: Temperature development (left) and vertical temperature profile at two time points (right) in the Murcia scenario.

It is clear from Figure 4 that the agreement between simulation results and experimental data is not as good in the PolyU/USTC case as in the two other experiments. Still, the results from the two simulation models corresponds rather well, even though the MZ model results in a slightly slower temperature development than FDS.

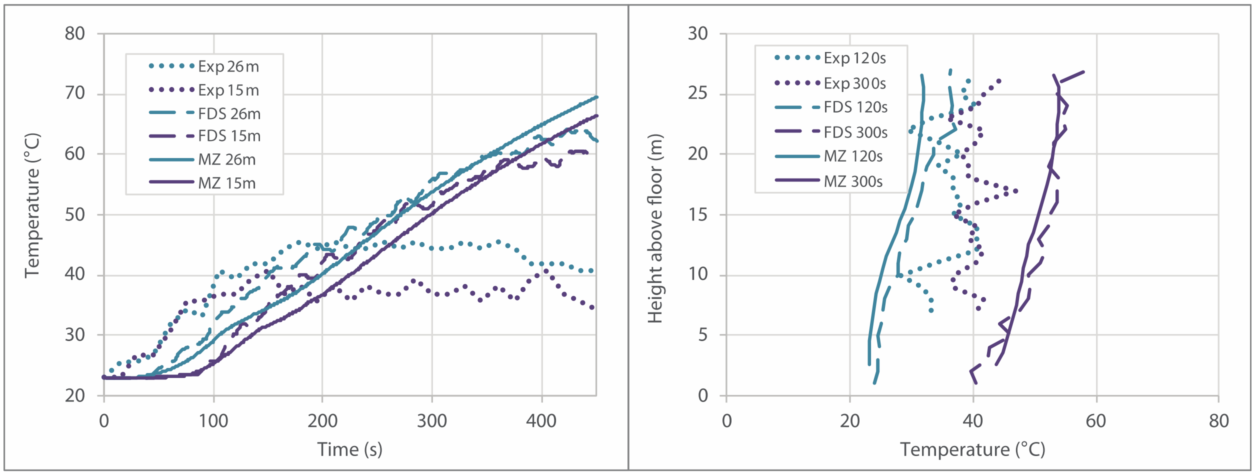

Figure 4: Temperature development (left) and vertical temperature profile at two time points (right) in the PolyU/USTC scenario.

Conclusion

If one recognizes that there is a gap between the simple but fast two-zone models and the more precise but time-consuming CFD models, the multi-zone concept might be of interest. The results presented in the evaluation study show that the MZ fire model predicts gas temperatures within 5% of FDS results and within 10% of the experimental data in two well-ventilated large spaces. In the third case there is a discrepancy between the modelling and the experimental data, the main reason for this is most likely the limited ventilation in the experimental test, that is not explained in any detail in the original description of the experiment.

The MZ fire model is simpler than FDS and is not as flexible. For example, the rather course zone resolution makes it difficult to include obstructions with fine details. There is no modelling of turbulence and the plume, that drives the flow of gases, is based on an empirical plume model. Still, there are clear benefits of the model. The main benefit is that simulations of scenarios like the ones used in the evaluation are performed within 1-2 minutes. This is in the order of 0.1% of the time to perform a similar FDS simulation on a desktop computer. The computation time for CFD simulations will most likely decrease with increased computer capacity, which might reduce the need for a quicker and less accurate tools like the MZ fire model. Nevertheless, the multi-zone concept is so much quicker that it still could be of value, especially for fire safety analyses in large spaces or as a part fire risk analyses, where hundreds of simulations might be needed. All in all, the results are promising and there might be a future for the MZ fire model; however, further studies are needed in order to quantify the accuracy of the model and its limitations.

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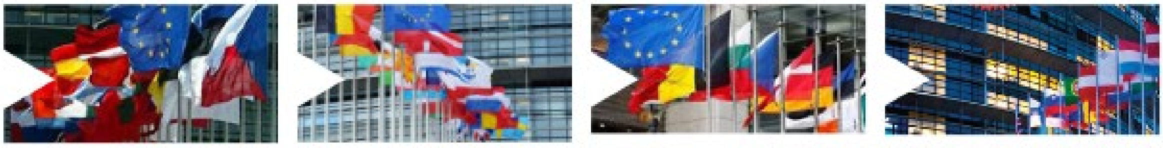

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IMPORTANCE OF SUPPORT CONDITIONS ON THE FIRE RESISTANCE OF CONCRETE FLAT SLABS

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Kate Nguyen, RMIT University, Australia

The use of concrete flat slabs in multi-storey buildings is increasing, and the current fire design guidelines for flat slabs are based on research carried out a few decades ago. In this work, the fire resistance of flat slabs was investigated at a large scale (3.78m x 4.75m) under structural loading and exposed to ISO 834 fire conditions. The test was also extended to investigate the behaviour during the cooling phase, as it is critical with restrained support conditions. Results show that the duration of fire resistance is significantly higher than that of similar tests with no lateral restraint. Heat propagation and deformation recovery during the cooling phase were also measured. Improved fire resistance duration suggests that the punching shear resistance is enhanced by restrained support conditions.

*This is a short version of the journal article titled 'Large-scale experiment on the behaviour of concrete flat slabs subjected to standard fire' published in Journal of Building Engineering [1].

Existing Design Practice for Fire Design of Concrete Flat Slabs

Current code-based approach to structural fire design of concrete flat slabs specifies a minimum thickness and a minimum cover to withstand a particular fire duration [2,3]. Thicknesses specified for flat slabs are considerably higher than thicknesses specified for conventional slabs with beams as flat slabs tend to due to punching shear near the slab-column connection (see Figure 1). However, the design guidelines are based on a limited number of flat slab fire tests [4-7] where most of the specimens are small-scale isolated specimens with no lateral restrains, except for one series of test that considered restrained support conditions on small-scale specimens [8].

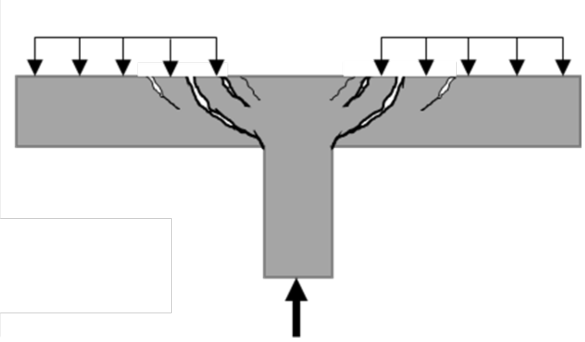

Figure 1. Typical punching shear failure of a concrete flat slab

Experimental Investigation on Fire Resistance of Concrete Flat Slabs

The authors tested a large-scale flat slab specimen (3.78m x 4.75m x 0.18m) under standard ISO 834 fire [9] with structural loading. Details of the specimen are shown in Figure 2 – 4. The supporting frame provided lateral restraints in order to more closely represent the continuous action of flat slabs in actual buildings.

Figure 2. Slab specimen with the supporting frame before placing on the furnace

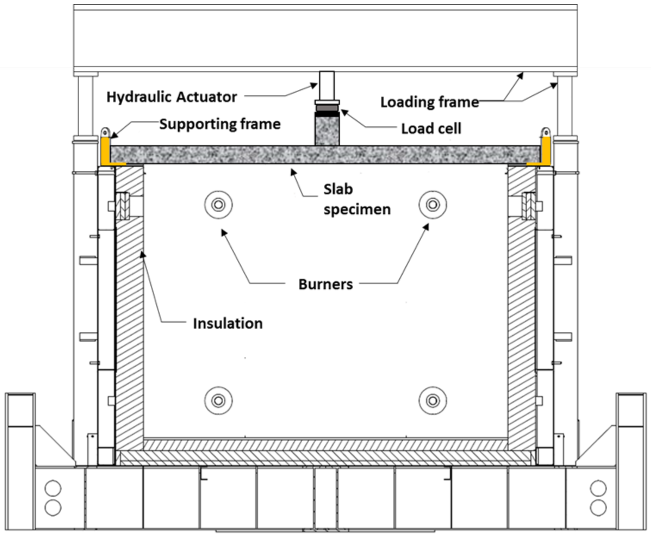

Figure 3. Test set-up

Figure 4. TCs, String pots and hydraulic actuator fixed to the specimen while it is on top of the furnace

Test Results and Discussion

The behaviour of the slab

The tension side of the slab specimen was exposed to ISO 834 standard fire, as shown in Figure 5.With the downward deformation due to heat, the pressure of the hydraulic actuator was dropping as the test started. In order to maintain the same load, continuous pumping was done while monitoring the load level. It was managed to keep the load level in the range of 225kN-275kN for 120 mins, with only a small drop, as shown in Figure 6. However, the length of the piston reached the limit at 120 mins, and therefore the load could not be maintained beyond this point

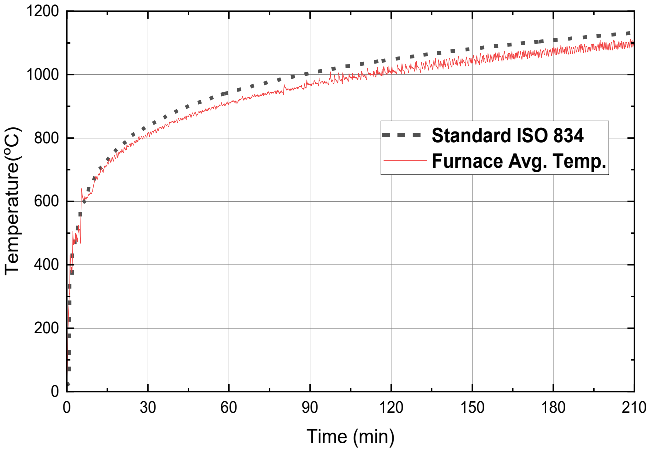

Figure 5. Temperature inside the furnace

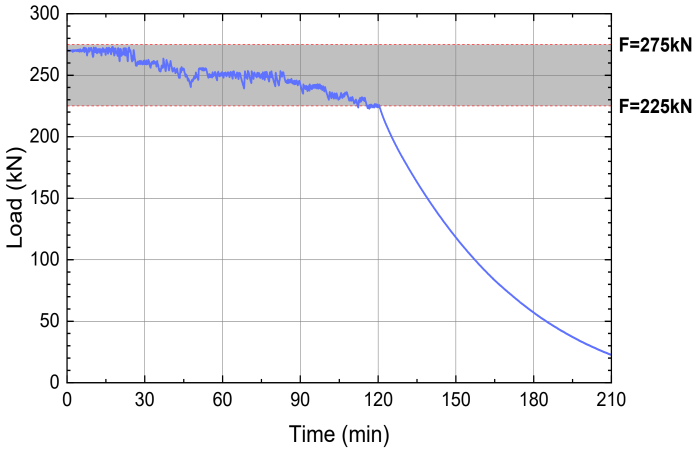

Figure 6. Applied load on the slab

Temperature Variation

Figure 7 shows the temperature recordings obtained from TCs fixed within the depth, as shown in Figure 4. It can be seen from the graphs that the exposed surface has reached a maximum temperature of 1000^{o}C at 3.5hrs, but the temperature of the unexposed surface is only 55^{o}C. It shows the good insulation characteristic of concrete, and importantly the unexposed surface temperature is well below the 180^{o}C limit specified by AS1530.4 [10] as the failure criteria for insulation. Furthermore, the measured temperatures are in close agreement with the temperature profiles for slabs given in EC2 part 1-2 Annex A [3].

Deflection

After heating commenced, downward deflection started to increase considerably, although the applied load was kept constant (see Figure 8). This implies that the deflection towards the fire was due to the thermal strain as a result of elevated temperature. Deflection at the centre was higher, and it decreases as it goes away from the centre as expected. Initial load was maintained until 2 hrs and the maximum deflection at that time was 85mm which is much less than the deflection limit ($L^2/400d$) for structural adequacy failure criteria specified by AS 1530.4 [10]. Therefore, it can be confidently stated that the slab has a fire-resistance period of 2hrs.

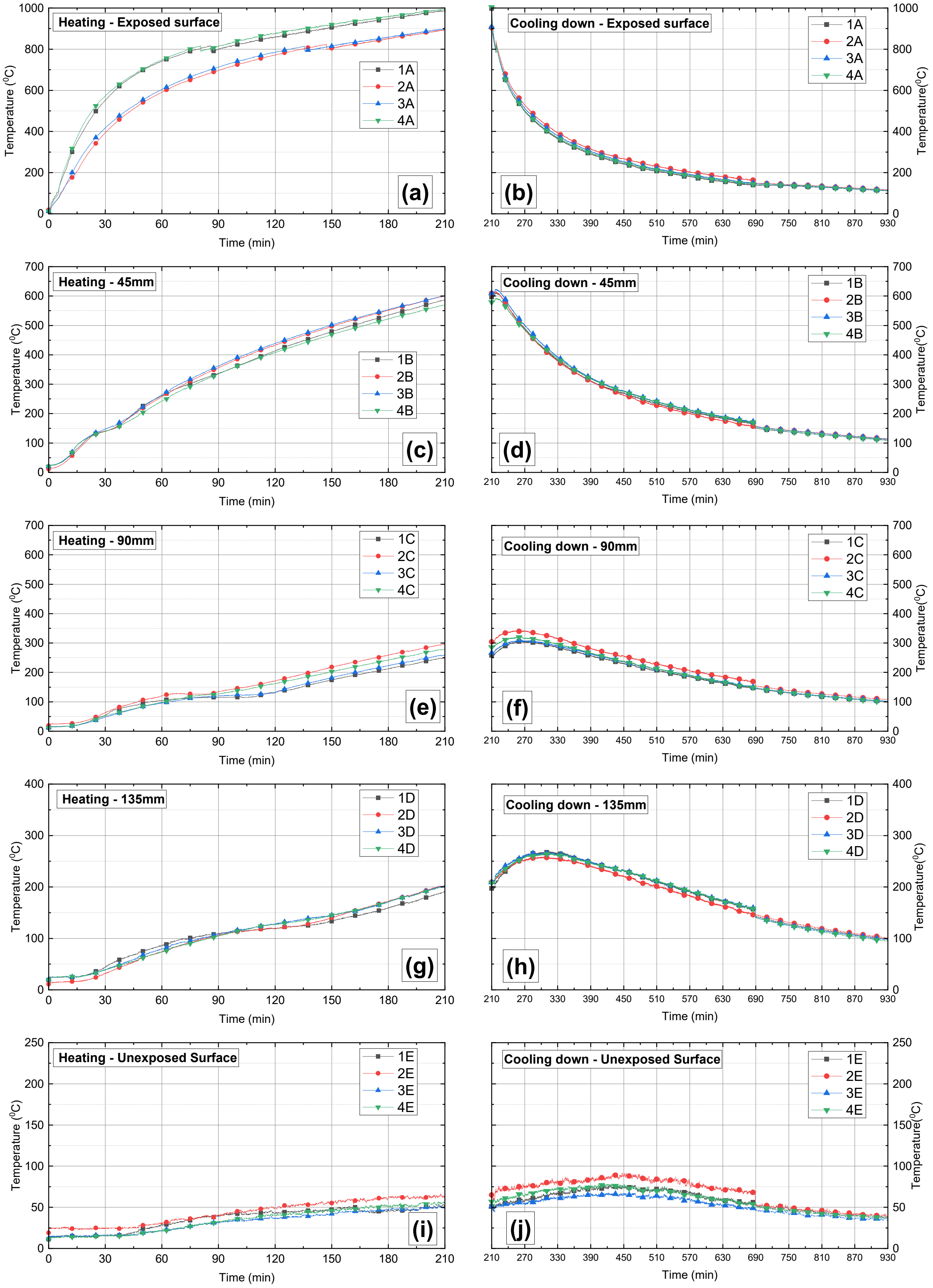
Heating - Exposed surface
Cooling down - Exposed surface
Heating - 45mm
Cooling down - 45mm
Heating - 90mm
Cooling down - 90mm
Heating - 135mm
Cooling down - 135mm
Heating - Unexposed Surface
Cooling down - Unexposed Surface
(a)
(b)
(c)
(d)
(e)
(f)
(g)
(h)
(i)
(j)
1A
2A
3A
4A
1B
2B
3B
4B
1C
2C
3C
4C
1D
2D
3D
4D
1E
2E
3E
4E
Temperature (^{0}C)
Time (min)
0
30
60
90
120
150
180
210
270
330
390
450
510
570
630
690
750
810
870
930
0
200
400
600
800
1000
100
300
500
700
50
150
250

Figure 7. Temperature variation of the slab during heating and cooling down. (a)exposed surface – heating, (b)exposed surface-cooling, (c)At 45mm-heating, (d) At 45mm-cooling, (e)At 90mm-heating, (f)At 90mm-cooling, (g)At 135mm-heating, (h)At 135mm-cooling, (i)Unexposed surface-heating, (j)Unexposed surface-cooling

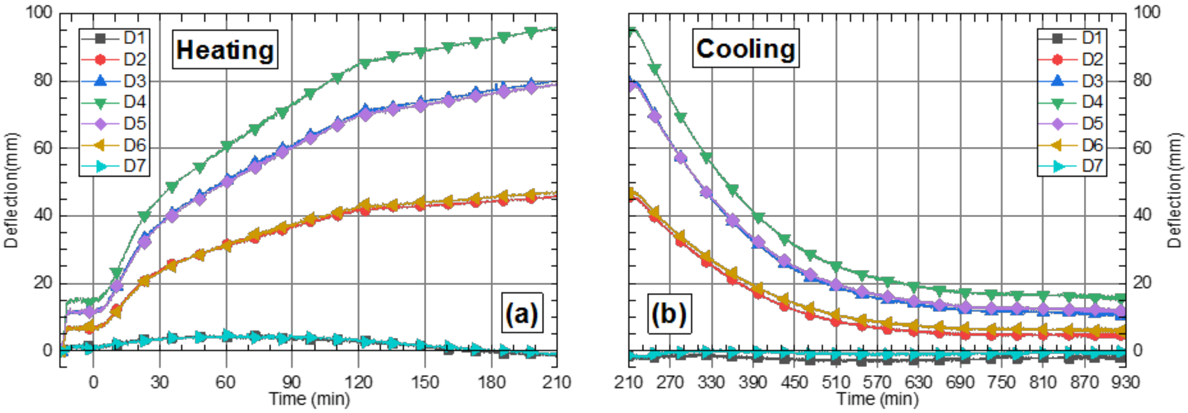

Figure 8. Deflection along the short span during (a)heating and (b)cooling

Fire Resistance

Fire resistance is defined as the time until the slab reaches one of the failure criteria for structural adequacy, integrity and insulation. The maximum deflection of 95mm reached during the heating phase is well below the L^2/ 400d failure criteria for structural adequacy. There were no visible cracks during that period. Although the slab was cured only for 28 days, there was no spalling during the complete test. Therefore, it is evident that the slab has passed the structural adequacy and integrity criteria during the heating phase.

In contrast to the guidelines specified by the design codes which requires to have a 200mm thick slab with 35mm axis distance to have a 2hr FRL, the 180mm thick slab used in the experiment with 35mm axis distance has survived more than 2hrs of standard fire exposure. Due to the lateral restraint against expansion, membrane action is allowed to develop during fire, and this could have influenced the enhancement in fire performance in this particular case. It closely represents the actual conditions in a building as the flat slab is continuous and adjacent slab panels could provide lateral restraint against heating; hence, membrane actions will be developed.

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