AUTHENTICATING CROWD MODELS FOR STADIUM DESIGN

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ABSTRACT

Crowd simulation software is an emerging technology used to validate and verify stadium design in terms of total egress and safe densities of large crowds. To model occupant movement, this technology can sometimes rely on dated and non-representative parameters. Where this limitation may be overcome with an array of movement input variables assigned by the user, currently these inputs lack diversity in profile representation. Limited studies have worked towards developing walking speeds for different demographics or are project-specific to stadium design. Even more limited are studies of complex profiles such as physical impairments and obesity. Circulation and evacuation models are therefore challenged in their ability to diversify crowd demographics and represent realistic demographic conditions. With realism not assured, there are a range of uncertainties that can be introduced by assumptions from the user.

To overcome these limitations, this research seeks to perform an analysis of the demographics seen at a stadium, establish a set of walking speeds, and use this to authenticate available egress simulation models. Herein, established behavioral profiles were used to represent children, young adults, adults, seniors, families, overweight adults, overweight seniors, as well as users of canes, crutches, and walking sticks, individuals carrying oversize luggage, and individuals requiring assistance. This data was then used to construct models in conventional crowd simulation software to compare with earlier modelling methods that assume the more dated and non-representative metrics for movement.

Individualizing profiles in total egress modelling provides a step towards reducing uncertainties of human behavior and producing more reliable frameworks for crowd movement predictions. The importance of diversifying input speed parameters is revealed in comparison to previously relied upon methods that limit crowd behavior to a single range of movement, and additionally, advocates for project-specific data acquisition. Current limitations of the models are discussed, and suggestions are made for continued studies on movement behavior and improvements to current software.

INTRODUCTION AND BACKGROUND

Stadia design is a unique area of engineering. Not only because stadia accommodate extremely large crowds – commonly in the tens of thousands – but more so because they must accommodate for the mass ingress and egress of these crowds, within short periods of time. This poses unique scenarios and credible areas of concern for practitioners, particularly regarding safety and accessibility.

Crowd simulation software is an emerging technology used to model and assess pedestrian dynamics of large crowds in stadia. This can be configured for regular circulation, ingress, egress, full and partial evacuations, and emergency situations. It is an important tool for practitioners in the validation and verification process of designing a safe usable space for people. This software allows the ability to specify parameters to simulate the desired movement scenario and populate the space with a desired population. Profile parameters are largely dependent on the walking speed in metres per second (minimum, maximum, mean, standard deviation) and radius in metres. Demographic distribution refers to the proportion of different profiles prevalent in the crowd.

Crowd simulation software is founded on the construction of behavioural profiles for people, and the construction of a 3D environment for these people to inhabit. Behavioral profiles are commonly based on social force or similar inverse steering algorithms, and are dependent on industry standard metrics, and project specific data input. These parameters however pose limitations on the functions and the outputs of crowd simulation models. This is because industry standard metrics are not always genuine to the specific population at hand, but rather use a generic distribution to describe the agents. Fruin Distribution, for example, is a commonly used metric that assigns speeds based on the density of the crowd. This results in flows tuned to math the data in John Fruin's Pedestrian and Planning design, based on studies produced nearly 50 years ago [1] [2]. And although the user can overcome some of these limitations by specifying an array of project-specific input data, this still poses some limitations. As discussed in the SFPE foundation on Movement and Anthropometry report [3] the required inputs currently lack diversity in movement representation, are relatively unavailable to use in practice, and are otherwise out of date.

Limited studies have worked towards developing walking speeds for different demographics; however, none (to the awareness of the authors) are project-specific to stadium design nor provide usable statistics regarding more complex agent profiles, such as those with physical impairments and obesity. Models are therefore challenged in their ability to diversify crowd demographics and represent realistic evacuations. With realism not assured, there are a range of uncertainties that can be introduced by assumptions from the user.

To overcome these limitations, this research, as supported through the SFPE foundation project on Movement and Anthropometry, works to configure four comparative crowd simulation models to analyse the impact of authenticating models with project-specific data as opposed to relying on industry standard metrics. Using a stadium event that takes place annually at York University, the authors analysed the crowd to establish a set of agent profiles and demographic distributions to model the following egresses:

Model 1: Current Default Parameters
Model 2: Manual Input Parameters for Average Population (Not Inclusive of Complex Profiles)
Model 3: Manual Input Parameters for Observed Population
Model 4: Manual Input Parameters for Forecasted Population

By simulating these models, the authors reveal the importance of using increasingly project-specific data and discuss the remaining limitations. The fourth simulation is additionally used to forecast modelling scenarios that work toward fully inclusive designs. Steps for model configuration and best practices used in crowd simulation software are also provided.

MODEL CONFIGURATION

The stadium considered in this study, is a tennis stadium located in York University, Toronto, Canada. It was built in 2004 and has a capacity of 12,500 people. Using this stadium enabled the authors to build off previous studies conducted at the same location, and use this data to produce the authentic models described in the later sections. Walking speeds were established for a variety of demographics observed at the event, placing particular focus on persons with mobility-impairments. All data collection was recorded using video footage analyses; thus, all cases were established using visually discernable cases. Further details to this data, and the method of collection, can be referred to in the SFPE foundation on Movement and Anthropometry report [3]. As within the foundation report, the authors advise that practitioners wait until the final papers on each infrastructure are released prior to utilising the movement speeds. These still require validation. In the mean time for research purposes such as those herein they are suitable to exemplify areas of further work.

The stadium was constructed to scale in AutoCAD using blueprints provided by the stadium officials (Figure 1), and then imported as a CAD file to MassMotion (MassMotion 2020, Version 10.5.6). All models simulate low-motivation scenarios, meaning they are not representative of emergency evacuations, for example. Pre-movement times were consistent in all simulations, based on the findings of Aucoin [4] in a Canadian stadium egress study. All models were given the same pre-movement parameters; a mean of 36 seconds, a standard deviation of 19 seconds, with a normal distribution. This enabled the authors to compare the models based on varying profile parameters and demographics distributions to isolate the impact of authenticating models with project-specific data to overcome limitations of industry standard metrics.

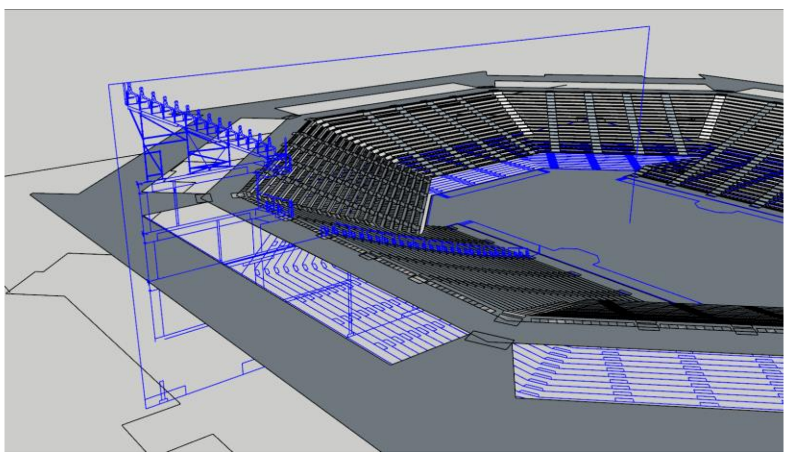

Figure 1. York University Model Generation.

<u>Profile Parameters</u>

The following table (Table 1) outlines the profile descriptions that are used in the simulations. This outlines the input speed and radius details that are required by the software. For modelling purposes, the profile radius is defined as half the distance from shoulder to shoulder, in meters [1].

The default profile speed and radius parameters are those which are pre-set and provided on default by the software. Using this software, the default settings describe the Fruin Commuter profile as the standard metric, which is commonly adopted in crowd simulation software.

The remaining walking speed parameters were derived through collected film footage by the authors. In 2018, the authors were granted access to the York University stadium for filming and interviewing attendees but were not allowed to manipulate ground conditions or invoke emergency conditions of egress. The building's site contained a pedestrian village with various restaurants, shops, and isolated events. This gave the authors a unique opportunity for the study of contemporary movement data sets of accessibility issues. Ethical considerations for filming were addressed by having each patron ticket explain that filming is taking place, disclosing this to attendees. The data collection method allowed the authors to consider vulnerable populations. Over the course of the summer, 1.7 TB of 1080p resolution video and a series of images were collected and studied to formulate movement profiles. Films were taken from carefully selected vantage points in the stadium and grounds using a series of Canon Mark III 5D cameras and GoPro 7s. Approximately eight students were required to participate in data collection. These recorded videos are still being studied by York University researchers for movement speeds and behavioral cues for final journal consideration. Figures 2 and 3 illustrates various locations of filming where data was derived from.

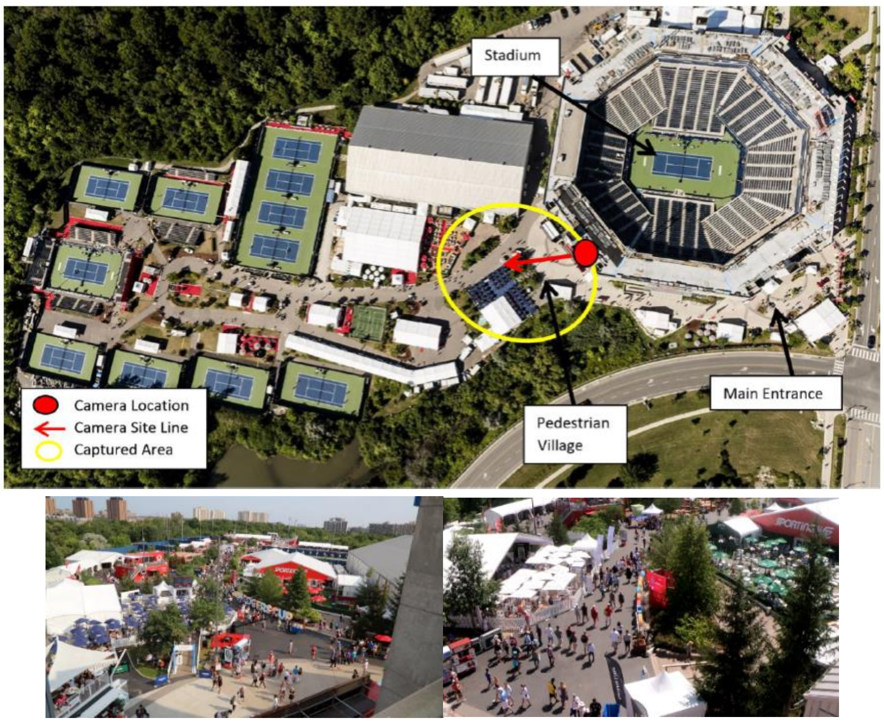

Figure 2. Toronto Tennis Stadium and Pedestrian Village Filming.

Figure 3. Toronto Tennis Stadium Selected Filming Angles.

The Able-bodied profiles are representative of average profiles for children (4yo-12yo), young adults (13yo-25yo), adults (26yo-64yo) and seniors (65yo+), all of whom are not subjected to any of the following mobility limiting impairments. Mobility-limiting impairment profiles include mobility cases that result from psychological or physiological abnormalities. This includes the use of a cane, crutches, walking stick and requiring assistance by another person, in addition to others which were not adopted for this study. Overweight and obese profiles are used to described adults, young adults and seniors who are overweight and/or obese. Other mobility limiting profiles are used for non-physical impediments, such as the use of oversized luggage. Some profiles were not adopted in this study such as intoxication which requires further research.

As seen in **Error! Reference source not found.**, the default radius is set to 0.25m, and within the manual, it is advised that any modifications to these parameters be within a range of 0.15m to 0.40m [1]. Data acquisition for radius parameters of the remaining profiles have not yet been established, nor are of accessible use to the authors. The authors therefore rationalized the respective radii using the above criteria and the existing footage (as above) to expand upon the SFPE foundation study [3] by analysing and approximating radius characteristics for the purpose of this study. The authors acknowledge that this is not an exact average, and further study is required to publish reference data.

Table 1. Agent Profile Descriptions.

	Speed (m/s)				
Agent Profile	**Min**	**Max**	**Mean**	**SD**	**Radius (m)**
Default Profile					
Fruin Commuter	0.65	2.05	**1.35**	0.25	**0.25**
Able-Bodied Profiles for Unimpeded Movement					
Child	0.34	2.25	**1.35**	0.75	**0.15**
Young Adult	0.71	2.61	**1.44**	0.58	**0.25**
Adult	0.67	2.75	**1.46**	0.59	**0.25**
Senior	0.40	2.42	**1.21**	0.48	**0.25**
Mobility-Limiting Impairment Profiles for Unimpeded Movement					
Cane	0.21	1.68	**0.91**	0.28	**0.35**
Crutches	0.35	1.22	**0.68**	0.34	**0.35**
Person Req. Assist	0.16	2.02	**0.98**	0.41	**0.40**
Walking Stick	0.14	1.68	**1.01**	0.41	**0.35**
Overweight and Obese Profiles for Unimpeded Movement					
Adult & Young Adult	0.60	2.32	**1.30**	0.54	**0.35**
Senior	0.46	2.11	**1.21**	0.63	**0.35**
Other Mobility-Limiting Profiles for Unimpeded Movement					
Oversize Luggage	0.08	2.62	**1.40**	0.55	**0.40**

[1] – Note that the maximum speeds differ from the SFPE foundational report [3] as outliers were removed

Demographic Distributions

To configure the comparative models using the previously defined agent profiles (Table 1), the following table (Table 2) outlines the demographic distributions assigned to each simulation. The total population for each simulation was set to 6250 people, which is half the capacity of the stadium. With the exception of Model 1 – the Current Default Parameters – the constructed models have adopted the agent profiles developed in the SFPE foundation study [3]. Models 2, 3 and 4 vary only by demographic distribution, meaning the characterized proportions of each population that is inputted to the software, which is described in further detail proceeding Table 2. We do not do a gender breakdown of this data as of current there are concerns of subjectivity in that analysis though this data is available. The data can also be more subdivided by age groups, however some data sets lose their statistical significance when this is done.

All models speak to standard egress motivation principles, meaning that they are not reflective of emergency evacuations. These models serve to analyse the limitations of current modelling methods and highlight the importance of collecting and inputting more detailed data for practitioner use. Note that they are presented as an illustration of the impact that project-specific data input has on authenticating models with crowd simulation tools and are not meant for design validation purposes.

Table 2. Demographic Distributions for Model Simulations.

	Model 1 (Default)		**Model 2** (Average)		**Model 3** (Observed)		**Model 4** (Forecasted)	
Agent Profile	**Frequency**		**Frequency**		**Frequency**		**Frequency**	
Default Profiles								
Fruin Commuter	100%	6250	-	-	-	-	-	-
Total	100%	6250	0%	0	0%	0	0%	0
Able-Bodied Profiles								
Child	-	-	15%	938	15%	938	14%	875
Young Adult	-	-	25%	1563	15%	938	12%	750
Adult	-	-	35%	2188	25%	1563	11%	688
Senior	-	-	25%	1563	10%	625	3%	188
Total	0%	0	100%	6250	65%	4063	40%	2500
Mobility-Limiting Impairment Profiles								
Cane	-	-	-	-	0.06%	4	2.82%	176
Crutches	-	-	-	-	0.01%	1	0.47%	29
Req. Assist.	-	-	-	-	0.09%	6	4.19%	262
Walking Stick	-	-	-	-	0.03%	2	1.40%	87
Total	0%	0	0%	0	0.19%	12	8.87%	554
Overweight and Obese Profiles								
Adult	-	-	-	-	22.58%	1411	34.95%	2184
Senior	-	-	-	-	11.00%	688	14.95%	934
Total	0%	0	0%	0	33.58%	2099	49.90%	3119
Other Mobility-Limiting Profiles								
Oversize Luggage	-	-	-	-	1.23%	77	1.23%	77
Total	-	-	-	-	1.23%	77	1.23%	77
Combined Total	100%	6250	100%	6250	100%	6250	100%	6250

Model 1: Current Default Parameters

This model illustrates the functions and outputs of current modelling applications that rely solely on industry standard metrics. It is the simplest simulation of the composed models. This model does not include any project-specific data on the population – no data is manually inputted for demographic distributions, speed parameters, nor radii – and instead, it uses the pre-set default parameters of the software. This model uses the Fruin commuter profile and distribution.

Model 2: Manual Input Parameters for Average Population (Not Inclusive of Complex Profiles)

Like Model 1, this model does not consider the vast diversity of movement profiles and instead limits movement representation to that of able-bodied profiles. It is slightly more authentic however, as it is built using the profile parameters and demographic distributions that were observed at the stadium event, as opposed to relying on industry standard metrics. Data was thus manually inputted for the proportions of able-bodied profiles (children, young adults, adults, and seniors) that were observed at the stadium event.

Model 3: Manual Input Parameters for Observed Population

This model is the most authentic and sophisticated simulation presented in this study because it was configured to reflect the observed population at the event as accurately as possible.

It is therefore an improvement on Model 1 and Model 2 by including a diverse set of profiles, not limited by distribution curves nor average populations. In addition to the able-bodied profiles, parameters were manually inputted for mobility limiting impairments (cane, crutches, persons requiring assistance, walking stick), overweight and obese profiles (young adults and adults, seniors), and other mobility-limited cases (oversize luggage). The demographic distributions were assigned based on the population proportions that were observed at the stadium event. The observed distributions of the more complex profiles were assigned first, and then these proportions were subtracted from the respective able-bodied profiles according to age.

Model 4: Manual Input Parameters for Forecasted Population

This model was constructed as an additional piece to give insight to inclusive design forums. Otherwise known as universal designs, these are environments that are optimized to meet the needs of all people. Essentially, it would be an environment that is fully accessible and offers equal service, availability, and opportunity for all people, independent of any mobility limitations one may posses.

The manually inputted profile parameters are the same data as seen in Model 3. As an extension of this however, the demographic distributions are not reflective of the observed population at the stadium event but are rather defined by a variety of national demographic statistics provided by Statistics Canada [5] [6]. By aligning the crowd demographics with those of the Canadian population, this theoretical crowd simulates the ideal diversity that inclusive designs aim to achieve.

Like Model 3, the demographic distributions were first assigned to the more complex profiles based on their prevalence in the population, and then subtracted from the respective able-bodied profiles. The main parameters used to define these distributions were that studies found mobility-related impairments to affect 1.6% of Canadians from ages 15 to 24, 7.3% from ages 25 to 64, and 24.1% over the age of 65 [6]. In another study, obesity was also found to affect 54.96% of Canadians from ages 18-64, and 68.2% over the age of 65 [5].

DISCUSSION

Using conventional crowd simulation software, each model was simulated 10 times, and the number of people egressed with time was recorded. The mean results were calculated for each model and graphed in Figure 4. The mean percent population egressed with time is additionally provided in **Error! Reference source not found.**3. Note that the models are in the introductory phase and are subject to subsequent (albeit slight) modifications, and thus the outputs presented below are preliminary findings and are terminated prior to conclusion of the slowest moving individuals.

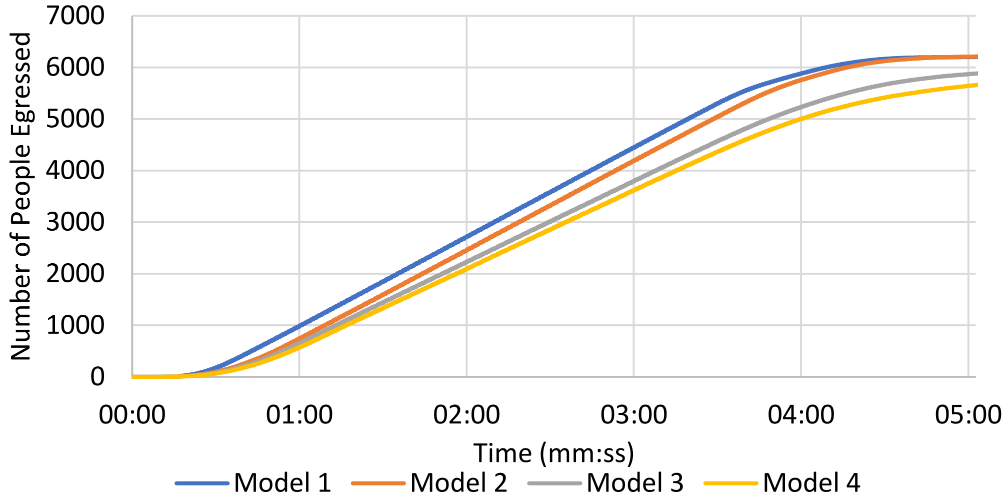

Figure 4. Graph of the Mean Number of People Egressed with Time for All Models.

Table 3. Mean Percent Population Egressed with Time for All Models.

Time (m:ss)	Percent Population Egressed			
	Model 1	**Model 2**	**Model 3**	**Model 4**
1:00	16%	12%	10%	9%
2:00	44%	40%	36%	34%
3:00	71%	67%	61%	58%
4:00	94%	92%	84%	80%
5:00	99%	99%	94%	90%

Model 1 shows the fastest egress, thus underrating the amount of time for the population to evacuate as the least accurate illustration of the evacuation. As anticipated, the overall time for egress increases as the demographic distributions are increasingly specified with each model. This is mainly due to the increasing proportions of profiles with reduced speeds and increased radii.

In comparison to Model 2, the accuracy of Model 1 at 3:00 minutes (3 minutes chosen as arbitrarily to compare the slope of each analysis where maximum percentage difference between the models were being observed- in future modelling all time stamps will be compared as the models are completed) is off by about 6%. This is because the mean speeds for able-bodied profiles are within the range of the default parameters (refer to **Error! Reference source not found.**), resulting in only a slight difference in egress time and observed behaviors.

Model 3 shows an even slower overall egress, along with unique pedestrian behaviors, based mainly on the fact that the newly introduced speed parameters are all slower, and the radii are greater. It is the most reflective model, considering it is based on real observations of the stadium crowds, and offers promising validation methods for design. Using project-specific details, this accurately reflects the expected population at the stadium. In comparison, the accuracy of Model 1 outputs at 3:00 minutes reduces by about 17%.

Model 4 shows the slowest overall egress, as the proportion of more complex profiles with slower speeds and greater radii increases drastically in comparison to the previous models. This shows the accuracy of Model 1 at 3:00 minutes is reduces by about 23%. This model highlights interest points in future stadium design, to better accommodate the vast population of persons with accessibility needs in Canada.

In conclusion, these calculations show how using the default parameters in Model 1 can severely underrate a required egress time. Although Model 1 shows strong results in comparison to the described distribution of average profiles in Model 2, this is not reflective of the many different movement capabilities observed in the present crowd illustrated by Model 3. Model 1 fails to acknowledge the more vulnerable portions of the population. Moreover, it is not a reliable method for simulating the demographic distributions seen in Canada's population in Model 4.

It is important to note that although this study presents ways to overcome some limitations of crowd modelling tools, additional research is still required to develop these tools further. Most notably, the presence of complex profiles is limited to those presented in Model 3 and 4, whereas there are many more profiles that would impact the functions and outputs of these models. This includes other mobility limiting impairments that are a result of psychological and physiological abnormalities such as cognitive deficiencies, mental health disorders, vision impairments, etc., and other movement behaviors that result from intoxication, cellular mobile usage, etc. This limitation is in part due to the lack of available movement data for the vast variety of profiles, and the inability of crowd simulation software to accurately incorporate said demographics. In addition to this, the crowd simulations presented in this study are defined by the architectural features of this stadium, meaning that these results and the impacts of relying on industry standard metrics would likely vary for a different environment. More specifically, this stadium consists of a relatively short travel distance in comparison to larger stadia. Therefore in other cases that the user is required to increase the travel distance, the size of the crowd, and/or the proportion of more complex profiles, the authors believe these will all contribute to increased egress times and different trends in human behavior.

PRELIMINARY CONCLUSIONS AND FUTURE RESEARCH

The preliminary models introduced in this study show promising results and reliability for future modelling methods. Preliminary findings on the amount of people egressed with time highlight the limitations of using a single profile distribution, in comparison to increasingly authenticated models that incorporate project-specific details on observed populations. The models presented in this study bring attention to the prevalence of varying movement abilities and how excluding them can lead to inaccurate results. Instead, these profiles must be included in modelling methods to accurately depict the population at hand, and work towards creating inclusive designs. As being considered by the authors, the stadium profiles and model will require validation against observed egress for additional confidence. In addition to the overall evacuation performance, independent demographics in the simulations are being analysed in terms of mean, minimum and maximum times for egress to give further detail to their movement behaviors in the crowd this may be concurrently compared to actual egress data. Future research should also expand upon the degree of accessibility movement considerations, such as to diversify available datasets to the inclusion of profiles with psychological abnormalities, other physiological abnormalities, intoxication, and mobile usage, to name a few. Further anthropometry effects should be considered as reviewed in the SFPE Foundation report. Lastly, a range of crowd modelling software typically used in stadium design should be considered.

ACKNOWLEDGEMENTS

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