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Transient reliability evaluation of a stochastic structural system in fire

Application of a probability density evolution method supported by evacuation models

Structural fire resistance is a fundamental component of the overall fire safety strategy for buildings. Specifically, with respect to life safety, the structural fire resistance is intended to allow for the safe evacuation of the occupants and access for the fire & rescue service. With the proliferation of performance-based design (PBD) methodologies, the efficiency of fire safety measures is increasingly being challenged. For low-rise buildings, with limited travel distances to a place of ultimate safety, evacuation may be very efficient, and from the perspective of life safety only limited structural fire resistance needed. For high-rise buildings with long evacuation times the opposite may be true. However, such interactions between structural and human response in fire are currently not clearly quantified, nor by extension explicitly considered in guidance. In support of rational decision making and cost-optimisation for (fire) life safety investments, the current paper tentatively explores the relationship between evacuation times in model office buildings on the one hand, and the time-dependent failure probability of critical structural components on the other hand. As a case study, the time-dependent failure probability of an insulated steel beam is evaluated, and the expected number of fatalities assessed for different model office building heights (i.e. affecting evacuation duration).

1 Introduction

Realising exceptional buildings necessitates that an adequate level of fire safety be explicitly demonstrated. This requires an evaluation of all foreseeable consequences, and the probability of their manifestation [1]. The probability of fire induced structural collapse is subject to numerous complex considerations, not limited to: (a) fire occurrence rate, (b) the prospect of early intervention by users, active systems, and / or the fire & rescue service, (c) the way the fire develops, and the associated stochastic factors, (d) the applied mechanical action at the time of the fire, and (e) the mechanical resistance of the structure at high temperature. Analogously, the factors influencing the consequences of fire induced structural failure are complex, with necessary consideration of: (i) the time of structural failure, (ii) building occupants present at the time of structural failure, (iii) what, if any, fire & rescue service activities are being undertaken at the time, (iv) the extent of damages to the property and assets therein, and (v) the extent of collateral damage to neighbouring property etc., dependent upon where a building is located, time of day of the fire event, etc.

Hopkin, et. al., [2] present recent studies that estimate failure probabilities of insulated steel members subject to fully developed fires. These failure probabilities, which are calculated in consideration of the burn-out of fully developed fires, are subsequently adopted in Van Coile & Hopkin [3] to estimate optimal failure probabilities given a significant fire via life-time cost optimisation. Within Van Coile & Hopkin, the failure consequences are not known in advance, nor readily calculable. As such, generalised optimal failure probabilities are presented in function of a damage-to-investment indicator, which broadly describes the ratio of failure costs to safety investment costs. Implicit within the former are the costs associated with loss of life.

This paper seeks to, firstly, estimate mortality associated consequences of fire-induced structural failures using a computational evacuation model, thus yielding relationships between time from ignition, and occupants remaining within five model office buildings. Subsequently, via an extension of the work presented in Hopkin, et. al., [2], failure probabilities as a function of time from ignition and mean fire load density are presented for protected steel elements subject to fully developed fires and afforded different insulation thicknesses.

2 Model Buildings

The model buildings feature compartments per that presented in Hopkin, et. al., [2] i.e. floor areas of 1,000 m^2, with an aspect ratio of 2:1. The floor to ceiling height is taken as 3.4 m, with a storey-to-storey height of 3.6 m. The model buildings are assumed to be used as open-plan offices, afforded two stairs – one to each end of the long axis of each building. The cases are differentiated only by the number of storeys and the associated impact on stair widths, i.e. (a) 6, (b) 8, (c) 12, (d) 16, and (e) 20 above ground storeys, respectively. The buildings are assumed to be located in England, and as such are designed to follow local guidance in the form of Approved Document B (ADB), Volume 2 [4].

3 Evacuation Study

The agent-based network computational tool Evacuationz (version 2.11.2) [5] has been applied for the computational evacuation modelling. The software applies the equations given in the SFPE Handbook given by Gwynne and Rosenbaum [6]. With specific reference to high-rise buildings, the tool has previously been compared to trial evacuation data reported in Kuligowski, et al. [7].

Five different evacuation cases are simulated per the model buildings (a) to (e) noted above. For each case, the stair widths have been calculated based on the recommendations of ADB, rounded up to the nearest 100 mm, and these widths range from 1,300 mm for the 6-storey model building to 1,700 mm for 20-storeys. To determine the stair sizing, an ADB recommended floor space factor of 6 m^2/person for offices has been applied, with occupants assumed to be split evenly between the two stairs when evacuating. All storey exits have been modelled with a total width of 0.85 m. No exits or stairs have been discounted or assumed unavailable for the simulations.

The Monte-Carlo method has been applied for 1,000 simulations per model building. This number of simulations has been determined to be broadly appropriate based upon convergence of the mean for total evacuation time.

Table 1 provides the key input distributions adopted for the computational evacuation modelling. The occupant density is derived from combined surveys of Milke and Caro [8] and Thackeray, et al., [9] for offices in the US, where guidance recommendations, including floor space factors, differ when compared to the UK. However, the assumed occupant density distribution incorporates a high maximum density and, therefore, in some instances, the generated occupancy will exceed the ADB design recommendation of 6 m^2/person for offices.

The pre-evacuation time has been selected from the work of Fahy and Proulx [10], for unannounced evacuation trials of a mid-rise office building with good fire alarm performance. The uncongested horizontal movement speed applies the data of Shi, et al., [11] for exit movement.

Table 1 Key computational evacuation modelling inputs

Input	Distribution	Distribution parameters
Occupant density	Truncated normal	Min: 0.5 m^2/person Max: 101.5 m^2/person Mean: 24.6 m^2/person Std dev: 14.1 m^2/person
Alarm time	Constant	Constant: 30 s
Pre-evacuation time	Triangular	Min: 0 s Max: 300 s Mode: 70 s
Uncongested horizontal movement speed	Triangular	Min: 0.8 m/s Max: 1.5 m/s Mode: 1.2 m/s

3.1 Evacuation Results

Figure 1 shows the probability density function (PDF) for the simulations for the total evacuation time of the 20-storey case. The time horizon is stated relative to ignition. Logically, as the time from ignition increases, the probability of large numbers of occupants remaining in the building progressively reduces.

The distribution of total evacuation time broadly follows a lognormal distribution, and this is consistent with results for the other model buildings (not reproduced herein). For the case in Figure 1, total evacuation times range from 12 min to 64 min, with a mean of 22 min and a standard deviation of 7 min. For comparison, the 6-storey case produces a mean time of 10 min, with a standard deviation of 7 min.

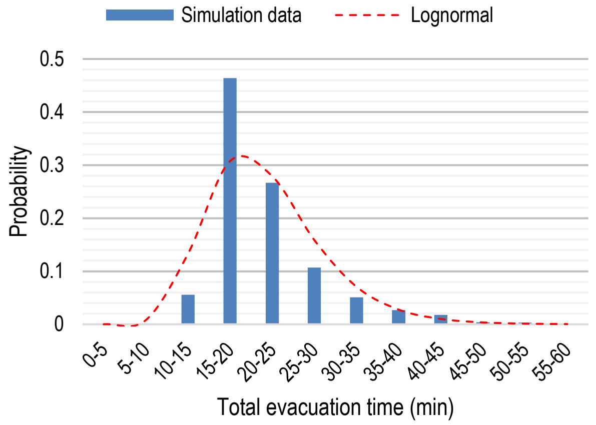

Figure 1 PDF for total evacuation time (20-storey case)

To consider the impact of time-dependent structural failure on building occupants, the number of simulated agents remaining within the building has been recorded at 5 min intervals. This is presented in the form of a cumulative density function (CDF), with the 20-storey case shown in Figure 2. For assistance in interpretation, for the 5-min case there is ~50% probability that 1,000 agents or less remain in the building. This increases to ~95%, after 25 min.

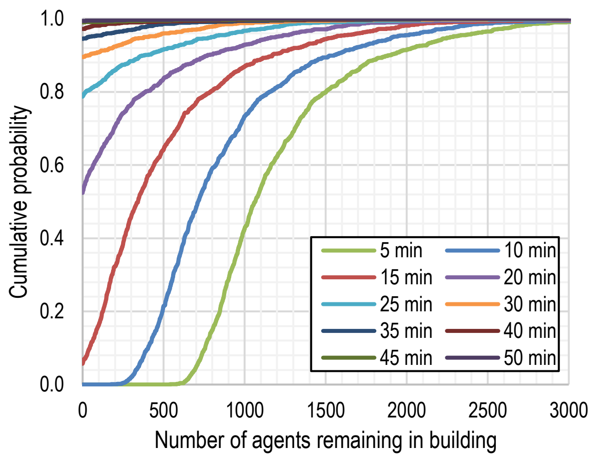

Figure 2 CDF for agents remaining in the building at 5 min intervals (20-storey case)

Figure 3 provides the mean number of agents remaining in the building at 5 min intervals for the five model buildings. As would be expected, the simulations indicate that the greater the number of storeys in the model building, the greater the mean number of remaining agents at a given time. For comparison, the mean number of agents remaining in the building at 5 min ranges from ~300 for the 6-storey model building to ~1,200 for the 20-storey model building.

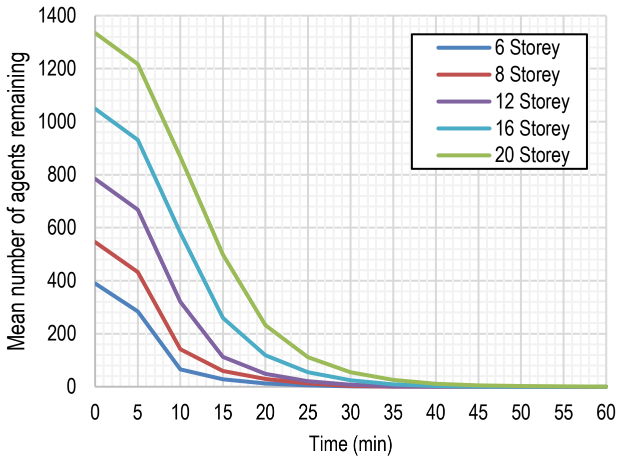

Figure 3 Mean number of agents remaining in building at 5 min intervals for all model buildings

4 Stochastic Structural Response Study

The structural response study is entirely independant of the evacuation study, and is evaluated on an elemental basis assuming the structural components are exposed to a enclosure fire within an compartment of volumetric dimensions as defined in Section 2.

4.1 Limit State

An element specific bending limit state is given by:

$$Z = K_R M_R - K_E \left(M_G + M_Q \right)$$

with the constituents as defined in Table 2.

Table 2 Parameters for bending limit state

Symbol	Name	Unit	Distribution	Mean (μ)	COV (V)
K_R	Model uncertainty for the resistance effect	-	Lognormal	1.10	0.10
M_R	Bending moment capacity	kNm	To be determined (see Section 4.3)		
K_E	Model uncertainty for the load effect	-	Lognormal	1.00	0.10
M_G	Bending moment induced by the permanent load effect	kNm	Normal	M_{Gk}	0.10
M_Q	Bending moment induced by the imposed load effect	kNm	Gumbel	0.2 M_{Qk} (5-year reference)	1.1 (5-year reference)

A generalised probabilistic limit state for steel elements subject to failure modes governed by yielding, i.e. pure bending or tension, is further developed in Hopkin, et. al. [2] from the above, resulting in the failure probability P_f of the structural element given a significant fire taking the form:

$$P_f = P(Z \leq 0) = P(k_{fy,ach} - k_{fy,req} \leq 0)$$

where $k_{fy,ach}$ is the achieved proportion of retained yield strength during a fire, and $k_{fy,req}$ is the required proportion of yield strength that must be retained given the actions imposed on the structure. The former is temperature dependent, the latter temperature independent.

4.2 Required Proportion of Retained Yield Strength

The PDF describing the required proportion of the yield strength, $k_{fy,req}$, depends upon the distribution of imposed and permanent loading, the proportions of these two loading components, model uncertainty in both the action and resistance models (as these are lumped together as temperature-independent stochastic variables), the ambient temperature yield strength, and section utilisation at ambient temperature. Considering the bending limit state above, it is shown in [2] that for a steel element subject to bending $k_{fy,req}$ is given by:

$$k_{fy,req} = \frac{K_E}{K_R} \frac{\left(M_G + M_Q \right)}{W_{pl} f_y}$$

with W_{pl} the plastic section modulus and f_y the ambient temperature yield strength. Within Hopkin, et. al., it is shown that $k_{fy,req}$ can be estimated assuming a lognormal distribution when the ratio of the imposed load effect to the combined imposed and permanent load effect (χ) is at most 0.50. This allows the distribution of $k_{fy,req}$ to be readily assessed through parameter estimation by Taylor expansion.

Herein, subsequent analyses presented in Section 4 are predicated on: (1) a fire (Eurocode design) utilisation (u_{fi}) of 42 %, yielding a (Eurocode design) limiting temperature (θ_{crit}) of 620 ºC, and (2) correspondingly, an ambient utilisation (u) of 80 %, with $\chi = 0.5$. Further background on the relationship between these core parameters is provided in Hopkin, et. al., [2] and Van Coile & Hopkin [3].

4.3 Achieved Proportion of Retained Yield Strength

$k_{fy,ach}$ is governed by the temperature attained by the protected structural elements within a given time horizon when subject to a fully developed fire, and also uncertainty with respect to the degradation of steel yield strength with increasing temperature.

Estimating maximum steel temperature necessitates that the fire environment be modelled. Within such fire models, there are numerous parameters which feature uncertainty and can be defined as stochastic variables, e.g. fire load, opening factor, spread rate, etc.

Herein, two fire models are adopted, a Eurocode Parametric Fire, and a travelling fire model (TFM) as proposed by Hopkin [12]. The required stochastic inputs differ between models, but are as adopted by Hopkin, et. al., as summarised in Table 3. The decision as to when to adopt a TFM over a parametric fire is dictated by the fire development characteristics. That is, the fire must spread to involve the compartment simultaneously, and the ventilation conditions should be such that the corresponding opening factor sits in the bounds of 0.02 – 0.2 $m^{1/2}$, with the opening factor as defined in Annex A of EN 1991-1-2 [13].

Conventionally when adopting a TFM for evaluating the full burn-out of an enclosure, the critical structural element location is known to be in the final third of the compartment length. However, where the failure probability is considered at different times from ignition, structural element locations along the entire compartment length must be considered. In the early phases of fire development, those elements nearest the point of ignition are most susceptible to failure. As the fire progresses, elements further along may be more severely exposed. Given this, three structural element location zones have been considered when adopting travelling fires: (a) first 1/3, (b) middle 1/3, and (c) final 1/3. The maximum element temperature attained for a given fire in any one of these location zones is taken as the critical case for the purpose of evaluating $k_{fy,ach}$. Where parametric fires are realised, element location is irrelevant as the enclosure is assumed to be at a uniform temperature, corresponding with a post-flashover condition. In both cases, steel temperatures are calculated using the lump-capacitance procedures in EN 1993-1-2.

Table 3 Stochastic Fire Variables

Input	Distribution	Parameters
Fire load density (MJ/m²)	Gumbel	Mean = variable, COV = 0.3
Heat release (kW/m²)	Constant	290
Glazing failure (%)	Linear	Range = 5 - 100
Near field temperature (°C)	Normal	Mean = 1,050, Std. = 64.5
Spread rate (mm/s)	Lognormal	Range = 5 – 19

Once the maximum structural element temperature is known for a given fire, the stochastic retained yield strength can be estimated from Khorasani [14], with distribution as shown in Figure 4. This figure indicates the relationship between retained yield strength and temperature, showing the mean retention factors, and corresponding variance from the mean through the addition or subtraction of one standard deviation.

4.4 Steel Fragility Curves

Steel fragility curves are output in function of the mean fire load density (qF - for a Gumbel distribution, with COV of 0.3), time from ignition, and are presented for different insulation thicknesses (dp).

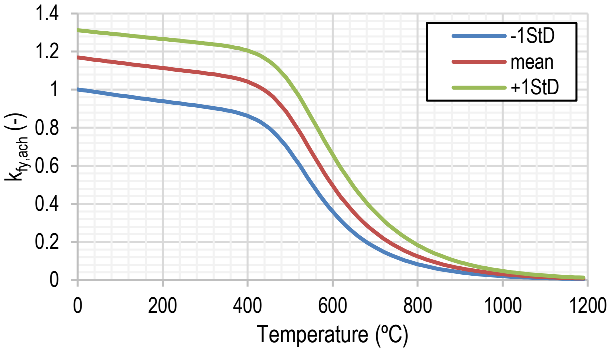

Figure 4 Temperature vs. residual yield strength based on Khorasani probabilistic Eurocode base model [14] – mean ± one standard deviation (StD)

Figure 5 and Figure 6 indicate the steel fragility curves as a function of the mean fire load density (presuming an insulation thickness of 5.2 mm) and insulation thickness (for qF = 400 MJ/m²). Both figures present failure probabilities in function of these parameters for different times from ignition. The former indicates a logical increase in failure probability with both time from ignition, and increasing fire load density. The latter demonstrates a redunction in failure probability with increasing insulation thickness.

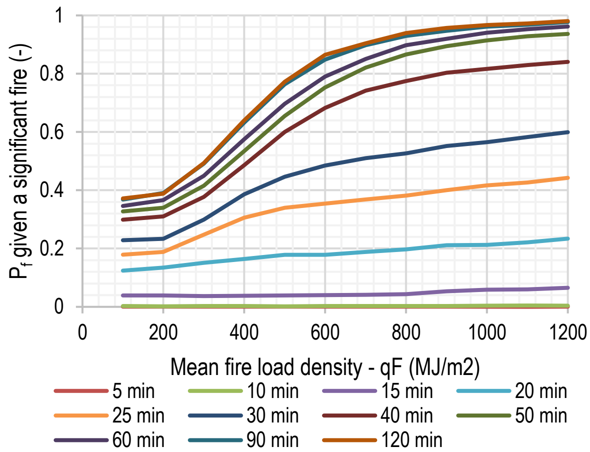

Figure 5 Failure probability given a significant fire in function of mean fire load and time from ignition – *dp* = 5.2 mm

4.5 Failure Rates and Relationship with Occupants

Failure rates, i.e. $\frac{dP_f}{dt}$, can be estimated from the relations shown in, for example, Figure 5 for a particular insulation thickness. The corresponding result is shown in Figure 7. The failure rate can be multiplied by a given fractile of occupants remaning for a given model building (e.g. mean), yielding a form of 'risk indicator' (RI).

$$RI = N_{rem}(t).\frac{dP_f}{dt}$$

An indicative relationship between time and risk indicator is shown in Figure 8, based upon the mean occupants remaining as indicated in Figure 3.

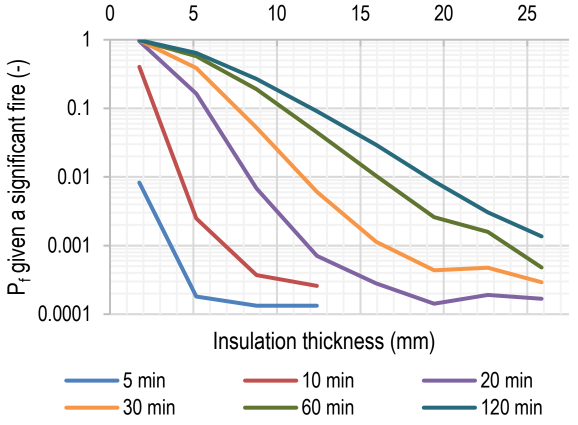

Figure 6 Failure probability given a significant fire as a function of insulation thickness and time from ignition – *qF* = 400 MJ/m²

Subsequently, the risk indicator can be integrated with respect to time (over the relevant burn-out time horizon) to give a form a 'risk rating' (RR):

$$RR = \int_0^t N_{rem}(t).\frac{dP_f}{dt}$$

The risk rating takes the units of remaining occupants, and is effectively a form of weighted occupancy that examines how many persons should be considered in the building if a fire induced failure occurs, when evaluated over a fire burn-out time horizon. For the data corresponding with Figure 8 (i.e. dp = 5.2 mm, and qF = 400 MJ/m^2), the corresponding RRs are: 6.3, 13.6, 25.7, 57.7 and 108.1 agents, for the 6, 8, 12, 16 and 20 storey cases, respectively. The ratings in isolation do not give a measure of the appropriateness of a design solution. However, the agent count can be input into life-time cost optimisation studies to establish what safety investment is justified.

5 Discussion & Further Work

Ambient temperature structural safety targets, such as those documented in ISO 2394 [15] vary in function of mortality associated consequence. More generally, Van Coile, et. al., [16] describe the ability to define safety targets in terms of a damage-to-investment indicator, albeit with the damage aspect also requiring an estimate of potential fatalities in the event of structural failure. It follows that for structural fire safety applications, the number of potential occupants within a building at the time of failure must also be estimated. This is not straightforward as: (a) fire induced structural failure is contingent on fire occurence, which could happen at differing times of day or year, (b) upon detection of fire, occupants receive an alert, and evacuation is conventionally instigated in some form, leading to uncertainty in the occupant number present, and (c) as occupants leave the building, the emergency services may be required to enter.

This initial study explores the interdependancy of the fire strategy (specifically means of escape), and the structural fire safety strategy. A computational evacuation model is adopted to give an insight into the stochastic relationship between time and potential remaining occupants for five model buildings, of varying height. In parallel, transient failure probabilities for protected structural steel elements are estimated in function of time from ignition, protection thickness, and mean fire load density.

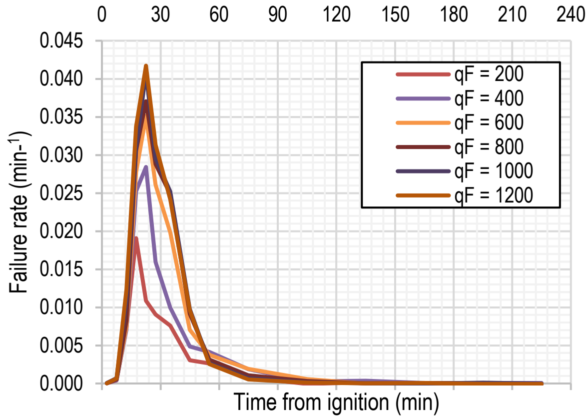

Figure 7 Failure rate vs. time from ignition, in function of mean fire load density *qF* (MJ/m²) for a 5.2 mm insulation thickness

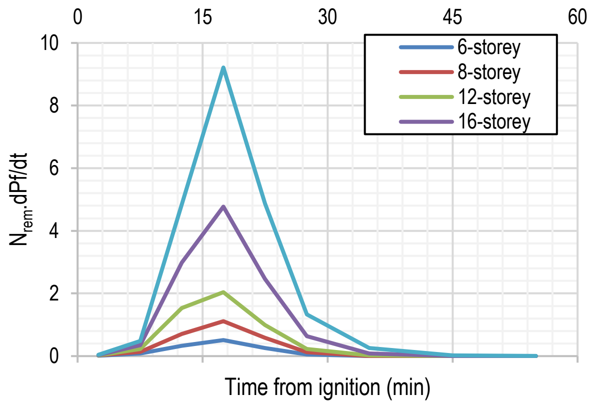

Figure 8 Risk indicator relative to time from ignition for the five model buildings based upon mean occupants remaining within given time frame – *dp* = 5.2 mm and *qF* = 400 MJ/m²

Logically, the two datasets indicate ascending and descending trends for structural element failure probability, and remaining occupants, with respect to time from ignition. Subsequently, a tentative risk indicator (RI) and risk rating (RR) is adopted, which relate the two fire strategy strands via the remaining occupant count and the structure failure rates given a significant fire occurence. The RI and RR, through life-time cost-optimisation methods (e.g. as in Van Coile & Hopkin [3]), could provide valuable new information for the purpose of both optimising fire safety investments, and also deriving explicit safety targets for fire exposed structures. In addition, direct relationships between insulation thickness and fire resistance period can be made, per [2], for comparison against National Guidance. Further work is required to refine the methods presented herein, in addition to consideration of how the implications of fire & rescue service access might also be captured.

References

[1] HOPKIN, D., VAN COILE, R., LANGE, D. (2017) *Certain Uncertainty-Demonstrating Safety In Fire Engineering Design & The Need For Safety Targets*. SFPE Europe, Issue 7

[2] HOPKIN, D., VAN COILE, R., FU, I. (2018) *Developing Fragility Curves & Estimating Failure Probabilities For Protected Steel Structural Elements Subjected To Fully Developed Fires.* 10th Int. Conference On Structures In Fire (Sif 2018). Belfast

[3] VAN COILE, R., HOPKIN, D. (2018) *Target Safety Levels For Insulated Steel Beams Exposed To Fire, Based On Lifetime Cost Optimisation.* The Sixth International Symposium On Life-Cycle Civil Engineering (IALCCE 2018). Ghent

[4] HM GOVERNMENT (2010) *The Building Regulations (2010) Approved Document B (Fire Safety) Volume 2: Buildings Other Than Dwellinghouses (2006 Edition Incorporating The 2010 And 2013 Amendments)*, London

[5] SPEARPOINT, M. (2017) *Evacuationz Emergency Movement Software,* Accessed 02 April 2018, From: Evacuationz.Wordpress.Com/

[6] GWYNNE, S., ROSENBAUM, E. (2015) *Employing The Hydraulic Model In Assessing Emergency Movement.* In SFPE Handbook Of Fire Protection Engineering, 5th Ed., Springer, Pp. 2115-2151

[7] KULIGOWSKI, E., PEACOCK, R., RENEKE, P., WIESS, E., HAGWOOD, C., OVERHOLT, K., ELKIN, R., AVERILL, J., RONCHI, E., HOSKINS, B., SPEARPOINT, M. (2014) *Movement on stairs during building evacuations.* TN 1839, National Institute of Standards and Technology, Gaithersburg, MD

[8] MILKE, J., CARO, T. (1997) *A Survey of Occupant Load Factors In Contemporary Office Buildings*, Journal Of Fire Protection Engineering, 8(4), pp. 169-182

[9] THACKERAY, T., MUHA, T., WOOD, T. (2012) *Evaluating Occupant Load Factors For Business Operations*, Undergraduate Project Report, Worcester Polytechnic Institute, US

[10] FAHY, R., PROULX, G. (2001) *Toward Creating A Database On Delay Times To Start Evacuation & Walking Speeds For Use In Evacuation Modelling*, 2nd Int. Symposium On Human Behaviour In Fire, Boston, USA, pp. 175-183

[11] SHI, L., XIE, Q., CHENG, X., CHEN, L., ZHOU, Y., ZHANG, R. (2009) *Developing A Database For Emergency Evacuation Model*, Building And Environment, 44, pp. 1724-1729

[12] HOPKIN, D. (2013) *Testing The Single Zone Structural Fire Design Hypothesis*. Interflam 2013, Proceedings Of The 13th International Conference. Royal Holloway

[13] CEN (2002) EN 1991-1-2:2002, *Eurocode 1: Actions On Structures - Part 1-2: General Actions - Actions On Structures Exposed To Fire*. Brussels

[14] KHORASANI, N. E. (2015) *A Probabilistic Framework For Multi-Hazard Evaluations Of Buildings And Communities Subject To Fire And Earthquake Scenarios*. PhD Thesis, Princeton University

[15] ISO (2015) ISO 2394:2015, *General Principles On Reliability For Structures*. Geneva

[16] VAN COILE, R., HOPKIN, D., BISBY, L. & CASPEELE, R. (2017) *The Meaning Of Beta: Background And Applicability Of The Target Reliability Index For Normal Conditions To Structural Fire Engineering*. Procedia Engineering, 210, pp 528-536

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