RELIABILITY RISK ASSESSMENT IN HIGH RISE BUILDINGS IN CASE OF FIRE

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ABSTRACT

The practice of structural fire safety engineering remains to be case-specific and the estimation of fire resistance of structures is mostly deterministic. Many researchers in structural fire engineering utilize the performance-based design method but these studies do not include the inherent uncertainties in both the demand and capacity. This paper investigates the structural fire reliability of tall buildings based on the framework used for earthquake hazard by the Pacific Earthquake Engineering Research (PEER) and Eurocode. The financial district of Istanbul in Turkey is taken as a case study for this research. Parameters such as building type and height, structural system, number of floors, floor area, number of elevators and stairs, the use of fire suppression systems, evacuation routes are provided by the municipalities in order to develop a probabilistic methodology to estimate the fire safety of these structures. The analysis is conducted by estimating the intensity or the hazard curve as described by PEER framework. The hazard domain includes random variables such as the fire load, the opening factor, the fire duration and the maximum fire temperature. The findings of this research will provide essential information on the fire safety risk of each tall building in a densely populated financial district. It will allow the municipalities and fire brigades to have a probabilistic risk assessment of these structures and develop evacuation and human rescue plans accordingly in case of a fire hazard. Further, this research will provide useful data to insurance companies to estimate fire hazard insurance premiums.

KEYWORDS

Structures in fire, structural fire safety and reliability, performance based design, probabilistic analysis.

INTRODUCTION

A number of fires in the 1960s and 1970s brought attention to the fire safety risk presented by high-rise buildings. Although fire hazards in very tall buildings are essentially the same as in low-rise buildings of similar uses (e.g., business, residential, mixed-use), the consequences of a fire have a potential to be more severe (Quiter, 2012). High-rise buildings differ from lower-height buildings in the following ways considering the fire safety:

- The time necessary for full building evacuation increases with building height. A special consideration must be provided in high-rise buildings employing assembly occupancies with large occupant loads on the upper floors to manage full evacuation.

- High-rise buildings have a greater potential fuel load, since their higher concentration of occupants, hence, more property loss.

- In emergency situations, there may be a delay in reaching the area to provide assistance, especially upper floors of a high-rise building.

- The existence of many individuals assembled in one location at any one time causes a rise of probability that some of these people could be injured or killed, because of a fire incident.

- Stack effect, which means the pressure difference causing temperature differentials between outside and inside temperatures gives birth air to move vertically, either upward or downward in a high-rise building. Subsequently, large uncontrolled fires may cause smoke as a result of the stack effect.

Since fire is such a low probability-high consequence event with considerable costs associated with protection, the use of performance based design frameworks accounting for multiple solutions is attractive, accounting for occupant and property protection. The performance-based engineering allows a broad spectrum of design solutions to be developed for different problems and evaluated based upon their individual merits by allowing either qualitative or quantitative risk of an event (Rini, 2008). Fire events and response of structures to such events involve a great deal of uncertainty. Performance-based design can be used to evaluate performance of a building under potential fire hazards while taking into account the inherent uncertainties in both the demand and capacity.

To predict the probabilistic response in the analysis of structures there have been recent developments by researchers in structural fire engineering area. For example, a review paper on the progress of the structural reliability evaluation in fire has been published by Beck (1985), Fellinger and Both (2000), and Khorasani et al. (2012). Guo et al. (2013) used Monte Carlo simulations to create a reliability-based design methodology. Guo et al. (2013) expressed all of uncertain parameters as random vectors in the reliability analysis. De Sanctis et al. (2011) developed a risk-based methodology for decision-making and representing the physical processes of a fire hazard by using a Bayesian probability network. By using first- and second-order reliability methods (FORM/SORM), a probabilistic approach to fire safety assessment and optimal design of passive fire protection on offshore topside structures is developed by Shetty et al. (1998). Hamilton (2011) Lange et al. (2014) adapted the earthquake framework, which is developed by The Pacific Earthquake Engineering Research (PEER) to structural fire engineering.

A probabilistic methodology is presented in this paper obtained by following the framework of Lange et al. (2014). The framework which is inspired by PEER's earthquake framework involves three main categories: hazard domain, structural response and loss domain, and each of these domains include random variables such as maximum fire temperature, deflection, strength and damage of structural components, however, compartment sizes expressed as deterministic. This paper illustrates a probabilistic risk assessment of high-rise buildings in case of a fire event in the light of the framework of Lange et al. (2014) by taking the maximum fire temperature as the intensity measure and also adding another level of uncertainty in the compartment sizes.

METHODOLOGY

Case Study

As a case study, a compartment by 9.5 m and 6 m from a tall steel building in Istanbul, Turkey is investigated as illustrated in Fig. 1. The 28-story tall steel building has a rather slender design with large-span compartments, and hence, it is an interesting case for structural fire safety. The steel building is designated as an office building. The compartment is designed a steel-framed (composite) floor, which consists of 120mm thick concrete slab with steel mesh reinforcement, four HE400A edge beams and two IPE330 secondary (internal) beams, which are connected to the edge beams with single plate bolted shear connections as denoted by blue circles in Fig. 1. The compartment is assumed to have 3.5m floor height, 1.5m window height (h_w) and 14.25m^2 area of opening (A_w), which gives the maximum opening factor as $F_{v,max}$ = 0.078 $\sqrt{m}$. For simplicity, all the boundaries of the compartment (walls, floor and ceiling) are taken as concrete with density ρ=2300 kg/m^3, conductivity k=1.5 W/mK and specific heat c_p=1000 J/kgK. A medium fire growth is assumed for the compartment.

Hazard Domain

The objective of this study is to estimate the fire hazard curve of a typical office-building compartment. There are several measures of the fire intensity such as the fire duration, the peak (maximum) temperature, the rate of heating and heat flux. As a preliminary step, the maximum temperature is taken as the intensity measure in the paper. For the calculation of the fire temperature-time history curve, the Eurocode parametric fire curve method is used (CEN, 2002).

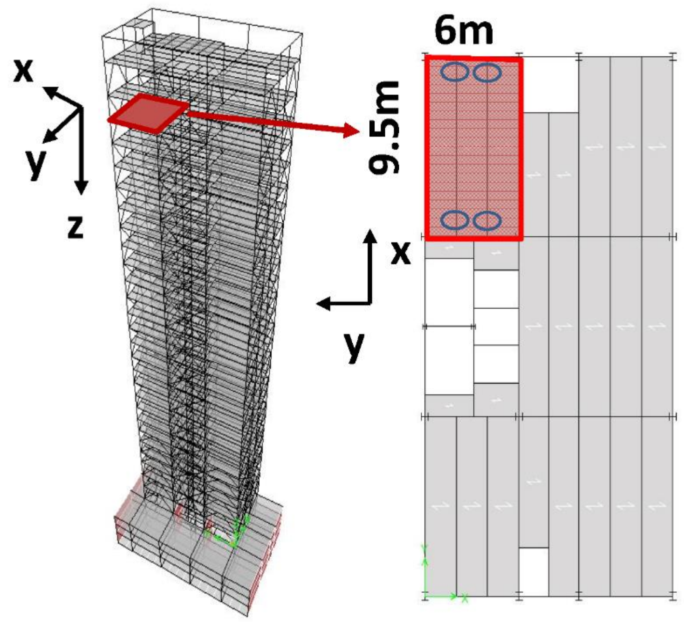


Fig. 1. Case study: (a) 28-story tall steel building and (b) the compartment floor layout.

Fire accidents and fire tests have shown that the thermal model is the most critical stage in the calculation of the temperature reached in a steel member, because, provided the heating rate of the steel member is accurately known, most mechanical models will predict similar deformation characteristics (Kay et al. 1996). There are number of factors for fire intensity measure. Recent papers have been considered duration of burning as fire intensity, however it is discovered that duration of burning is not adequate, fire severity may be a better option to measure intensity of fire. Fire severity can be expressed in terms of parameters such as rate of increase in the temperature in a compartment, duration of the steady burning phase, or peak temperature, heat flux, etc (Lange, 2014). In this study, the peak temperatures from Eurocode parametric fire curve (CEN 2002) are considered. This parametric fire curve gives different time-temperature relationship for a given compartment size, lining materials (e.g. concrete, gypsum wall, brick) and the ventilation openings. The fire is assumed to be a post-flashover fire, which is critical for the structural members. The fire could be ventilation or fire controlled.

RESULTS AND DISCUSSIONS

A Matlab code is written to generate the random variables and to calculate the fire curves according to the Eurocode parametric fire method. The code also checks for ventilation and fuel controlled fire. If the burning period is less than t_{lim} = 20 minutes (medium fire growth), the duration of the heating phase is set to t_{lim}.

Although the specific compartment sizes (9.5m by 6m) are taken, the dimensions are varied by Normal distribution (Eq. 1) using 9.5m and 6m as mean (μ) values, respectively. For both long and short dimension, the same scale factor σ= 3m is used. This scale factor is hypothetical. The goal is to generate a large variation in compartment sizes. The compartment size distributions are shown in Fig. 1. Due to computer speed and memory limitations, 100 samples of each size dimensions are randomly generated. For each sample, the maximum temperature probability density function calculated as described in the following paragraphs.

$$p(compartment\ dimensions) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{(x-\mu)^2}{2\sigma^2}} \tag{1}$$

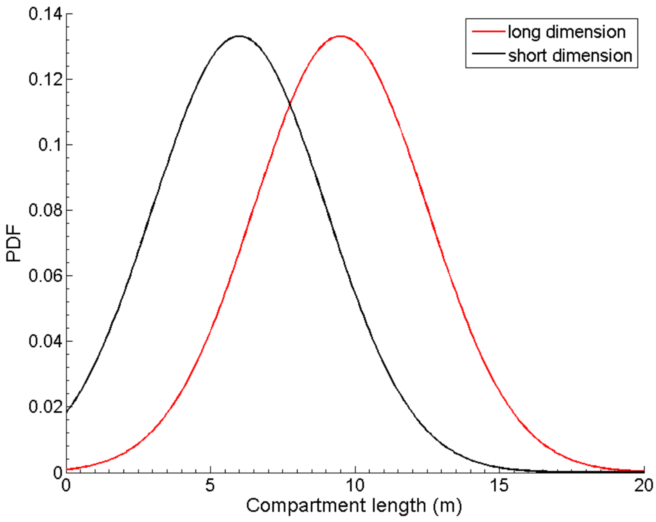


Fig 1. The probability density function of the compartment sizes as Normal distribution.

In Eurocode parametric fire curve method, the characteristic fire load density on the compartment floor (q_k – MJ/m^2) is taken as a random variable and 10,000 samples are generated. The design fire load (q_d) as suggested by Eurocode 1 (CEN 2002) is not used and the effect of the active fire measures are considered when calculating the annual rate of occurrence of fire in later sections. As suggested by Eurocode, the probability density function for the fire load in an office building is taken as Gumbel distribution as in Eq. 2 with mean (μ) of 420 MJ/m^2 and standard deviation (σ) as 126 MJ/m^2, which gives 511 MJ/m^2 as 80% fractile. Table 1 shows the fire load densities for different building categories. Fig. 2 shows the probability density function of the fire load (q_k). The randomly generated numbers are superimposed on the plot.

$$p(q_k) = {}^{1}/_{\sigma}\, e^{-(z+e^{-z})} \tag{2}$$
$$where\ z = {}^{(x-\mu)}/_{\sigma}$$

Table 1 Data on fire load density for different buildings [MJ/m²] (Fitting with a Gumbel type I distribution)

	Standard Deviation	Mean	80 % fractile	90 % fractile	95 % fractile
Dwelling	234	780	948	1085	1217
Hospital	69	230	280	320	359
Hotel (room)	93	310	377	431	484
Library	450	1500	1824	2087	2340
Office (standard)	126	420	511	584	655
School	85,5	285	347	397	445
Shopping centre	180	600	730	835	936
Theatre (cinema)	90	300	365	417	468
Transport (public space)	30	100	122	139	156

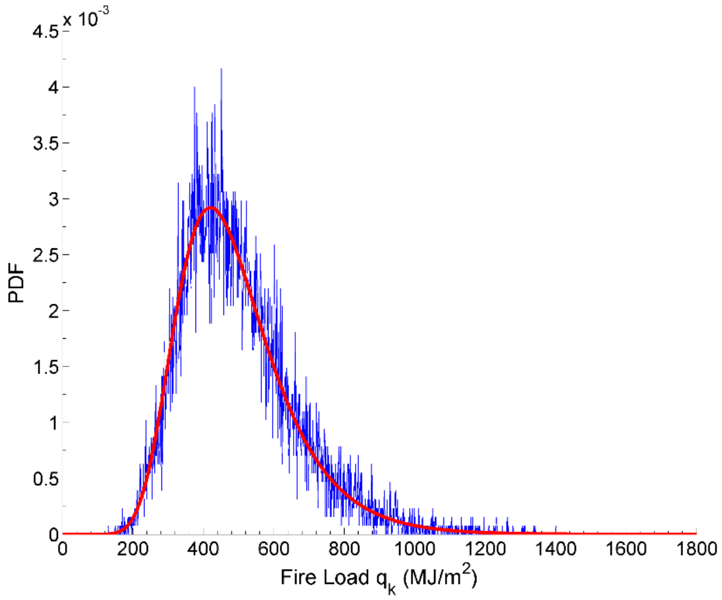


Fig 2. The probability density function and histogram of the fire load as Gumbel distribution.

The opening (ventilation) factor F_v ($\sqrt{m}$) is taken as a random variable and 10,000 samples are generated. The maximum opening factor $F_{v,max}$ is taken as constant, which depends on the given window areas in the compartment. However, the actual opening factor F_v is varied with ξ as shown in Eq. 3 suggested by Joint Committee on Structural Safety (CEN 2002).

$$F_v = (1 - \xi)F_{v,max} \tag{3}$$

The probability density function for the opening factor is taken as Log-Normal distribution with mean (μ) 0.2 $\sqrt{m}$ and standard deviation (σ) 0.2 $\sqrt{m}$. The distribution is truncated at 1.0, since the value of F_v cannot be negative. The associated μ and σ for the normal distribution are -1.956 and 0.833, respectively. Fig. 3 shows the probability density function of the variation in the opening factor load (ξ). The randomly generated numbers are superimposed on the plot.

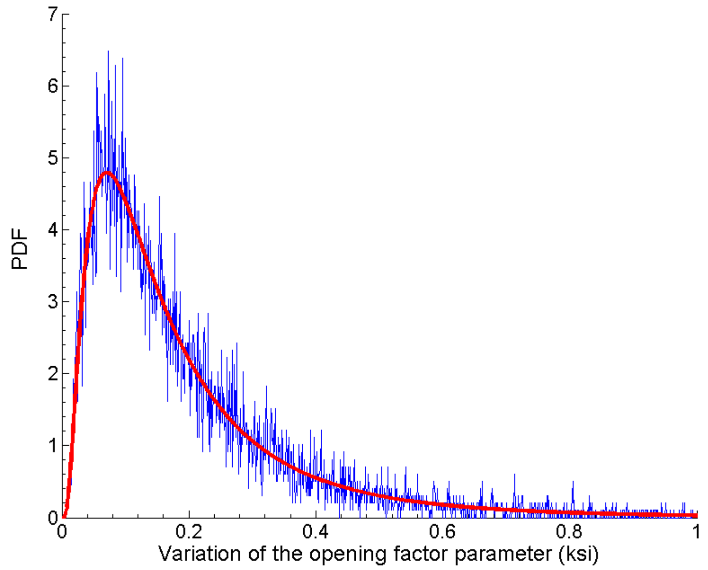


Fig 3. The probability density function and histogram of the variation in the opening factor as Log-Normal distribution.

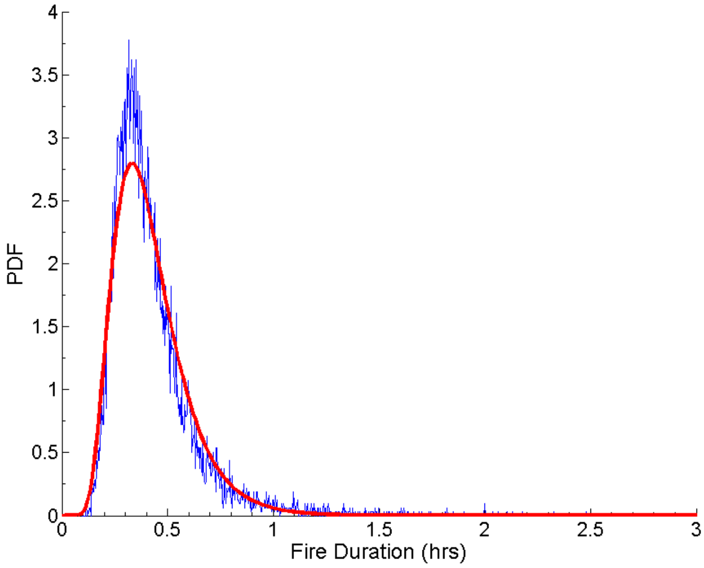


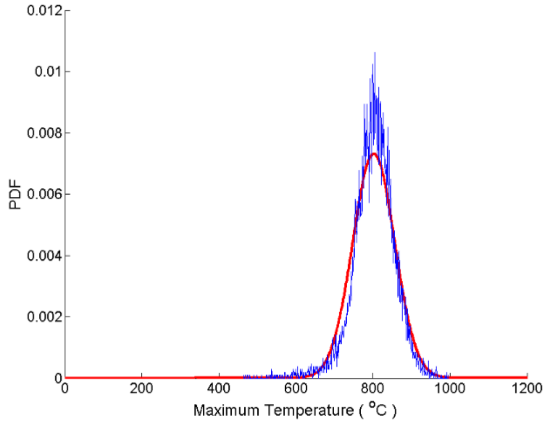
Fig 4. The probability density function and histogram of the fire duration as Log-Normal distribution.

With random sampling techniques using the fire load and the opening factor, the probability density function of the fire duration is created as seen in Fig. 4, which has a shape of Log-Normal distribution with mean (μ) 0.42 and standard deviation (σ) 0.03. By knowing the distribution of the fire duration, the maximum temperatures are readily calculated. As in Fig. 5a, the probability distribution function of the maximum temperatures resembles the Normal distribution with mean (μ) 802 °C and standard deviation (σ) 54.6 °C. The annual rate of exceedance of the maximum temperature in this compartment is found by multiplying the annual rate of occurrence in an office building (r_{fi}) with [1-P(T_{max})], where P(T_{max}) is the cumulative distribution function of the maximum temperature distribution as shown in Fig. 5a. The annual rate of exceedance r_{fi} is calculated according to Natural Fire Safety Concept (Schleich 2001) given in Eq. 4. Eq. 4 gives the annual rate of exceedance per m^2 floor size.

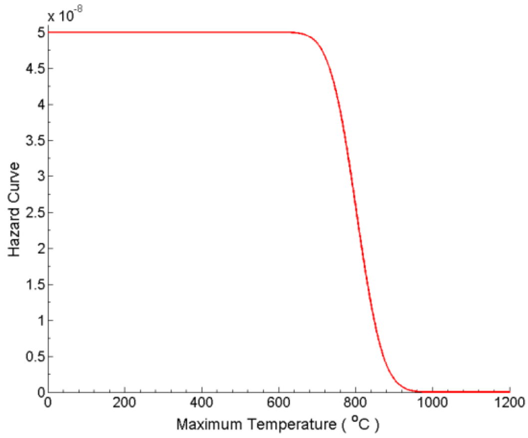
$$r_{fi} = p_1 .\, p_2 \,.\, p_3 \,.\, p_4 \tag{4}$$

Here, the p values are probabilistic measures, which depend on the active fire mechanisms such as building occupancy category (p_1= 4x10^{-7}) fire brigades (p_2 =1.0), smoke alarms (p_3 = 0.0625) and sprinklers (p_4=1.0) as suggested by Lange et al. (2014). Fig. 5b shows the corresponding hazard curve of the probability of exceeding a given maximum temperature in the compartment. The probability that a fire (with flashover) will break out in the compartment is 5x10^{-8}. If the fire breaks out, the probability that the maximum fire temperature in the compartment is greater than 650 °C is 1.0, which might be a critical temperatures for the load-bearing structural members. However, maximum temperatures greater than 900 °C is unlikely to occur.

If the compartment sizes are varied as shown in Fig. 1, the probability density function of the maximum temperature in the compartment slightly shifts to the left and its standard deviation gets larger when compared to the curve with determinate compartment size. The probability density function with randomized compartment sizes fits to a Normal distribution with mean (μ) 781°C and standard deviation (σ) 83°C as shown in Fig. 6. The corresponding hazard curve is shown in Fig. 7. The annual rate of occurrence r_{fi} (per m^2 floor size) is taken constant as previously suggested. The hazard curve suggests that given the fire breaks out, as low as 600 °C and as high as 1000 °C maximum temperatures are expected. The comparison suggests that in case of a post-flashover fire, the compartment is likely to have lower temperatures if the compartment sizes include some uncertainty. If the entire building is considered with total floor size of 13,200m^2, the annual rate of fire occurrence becomes 6.6x10^{-4}.



(a)



(b)

Fig 5. (a) The probability density function of the maximum temperature in the compartment and (b) the corresponding intensity measure hazard curve of the annual rate of exceedance of the maximum temperature (per m^2 compartment).

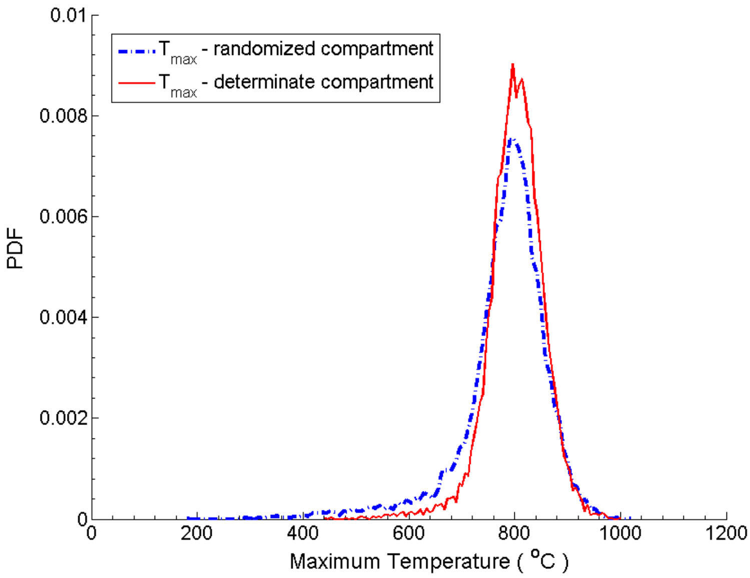


Fig 6. The probability density function of the maximum temperatures as Normal distribution with determinate compartment size and randomized compartment size.

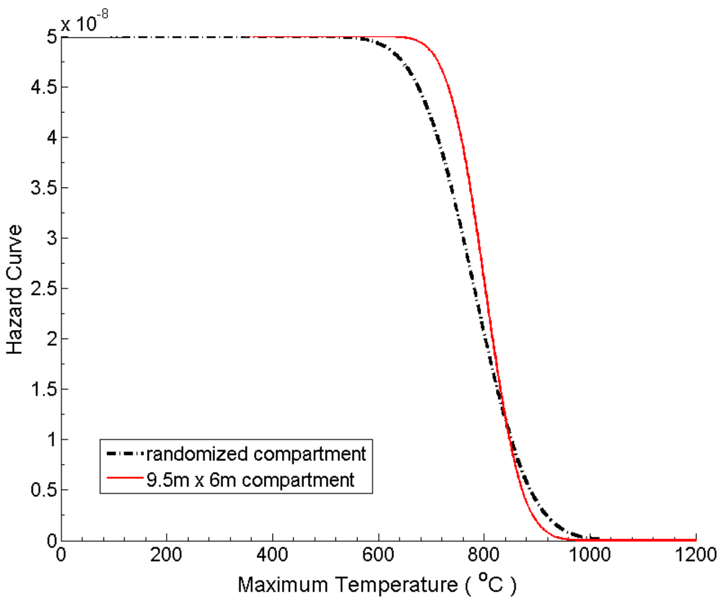


Fig 7. The intensity measure hazard curve of the annual rate of exceedance of the maximum temperature (per m^2 compartment).

CONCLUSIONS

In this paper, a probabilistic approach to structural fire engineering is investigated. The study applies PEER performance based earthquake engineering framework for structures in fire. As a preliminary study, the paper only estimates the intensity measure, which is assumed to be the maximum fire temperatures in the compartment of a 28-story steel building. The results show that the annual rate of exceedance of maximum fire temperature T_{max} > 650 °C is $5x10^{-6}$ and the temperature T_{max} > 900 °C is very unlikely to occur. If the uncertainties in compartment sizes are also included in the analysis, it is observed that the annual rate of exceedance of maximum fire temperature T_{max} > 650 °C is $4.65x10^{-6}$ and the temperature T_{max} > 1000 °C is very unlikely to occur. This result suggests the probability of a very severe fire increases with the uncertainties in the compartment sizes.

Future work will expand this study in several ways. First, the intensity measure will be changed to steel or concrete mean section temperatures, since the structural response is better represented by the material's temperature rather than the fire temperature of the compartment. Next, the structural response of typical steel-framed composite floors will be estimated by considering the floor deflection as the engineering demand parameter.

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