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FIRE RISK ASSESSMENT OF MULTI-STORY BUILDINGS BASED ON FRAGILITY ANALYSIS

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ABSTRACT

Recent efforts aim at assessing the fire performance of structures in a probabilistic framework. But there is still no well-established method to quantify the reliability of entire buildings. Previous works focused on isolated structural members, therefore not allowing for a determination of the global safety level of buildings. Here, a new methodology is developed to quantify the reliability of buildings in fire. The methodology uses Monte Carlo simulations for constructing fragility functions associated with different fire breakout locations in a building, then combines the functions to characterize the overall building conditional probability of failure, and finally incorporates the probabilistic models for intensity measure and fire occurrence likelihood. The methodology is applied to multi-story steel buildings. This work addresses fire reliability at the building scale, and therefore is useful for standardizing safety level as well as for evaluating community resilience.

1 INTRODUCTION

Recently, the approach in fire safety engineering is moving toward a probabilistic framework, where uncertainties in variables are explicitly accounted for and the safety level can be quantified. The literature describes methods for probabilistic analysis of steel [1, 2] and concrete [3, 4] structural members under fire. However, these methods address the fire reliability of isolated structural members rather than complete structures, and additional efforts are needed to develop a methodology that incorporates the uncertainties in fire occurrence, fire development, heat transfer processes and structural response at the building scale.

The authors developed a method to generate fire fragility functions providing a probabilistic measure of vulnerability for an entire building system [5]. Fragility functions yield the probability of exceeding a damage state (e.g. column failure, excessive beam deflection, etc.) for a given

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intensity measure of the hazard (here: fire). They have been largely adopted in other fields such as seismic engineering, notably because they fit well into performance-based probabilistic frameworks in which one wants to separate between the hazard analysis and the structural analysis [6].

This paper describes how the fire fragility functions can be incorporated into a broader methodology to assess the risk related to structural failure due to fire for multi-story buildings. Specifically, the functions are combined with probabilistic distributions for the intensity measure and probability of occurrence of a fire. This allows obtaining the (annual) probability to reach different levels of potential damage for buildings of different typologies, structural design, size and occupancy. The methodology is illustrated on prototypes multi-story steel buildings.

2 METHODOLOGY FOR FIRE RISK ASSESSMENT

2.1 Overview

The methodology to assess the fire risk of buildings is described in *Fig. 1*. Damage States (DS) need first to be defined, which are indicative of 'failure', or indicative of any threshold in the magnitude of the damage which is significant to the user.

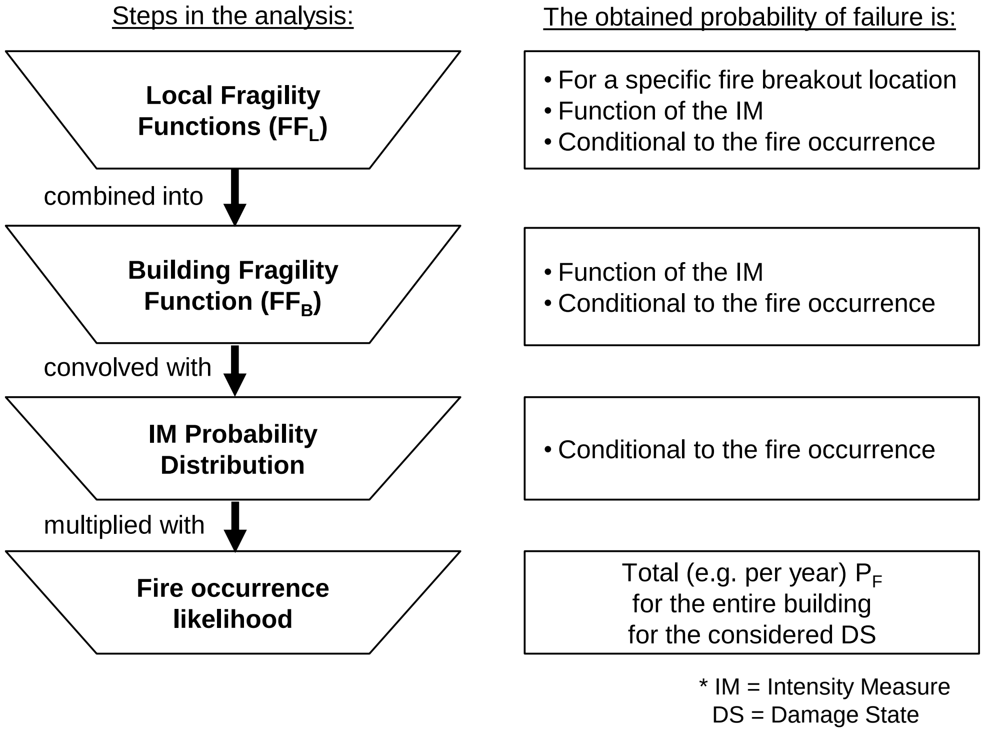

Fig. 1. Methodology to assess the probability of failure (i.e. reaching a predefined damage state) due to fire for multi-story buildings, using fragility functions.

The methodology relies on the development of fragility functions. The functions are first constructed at the local (i.e. compartment) scale, assuming a fire scenario in a well-defined compartment; this leads to different functions (FF_L) for each compartment. Then, these functions are combined into a single building fragility function (FF_B) that characterizes the overall vulnerability of the building (regardless of the fire location). By definition, the fragility functions yield the conditional probability to reach a DS as a function of the fire intensity as measured by an Intensity Measure (IM). The dependence on the IM can be eliminated by adopting a probability density function (pdf) for the IM and convolving the fragility functions with this IM pdf. This yields a single value (scalar) for conditional probability of failure. Finally, the probability of occurrence of a fire in the building can be estimated and multiplied by the conditional probability of failure, which results in a total probability of failure (P_F) for the entire building, for the considered DS. In other words, the probability that the damage state will be reached somewhere in the building, due to fire, over the period considered (e.g. per year) is obtained.

2.2 Fire fragility function for one compartment - FF_L

As a first step, fragility functions FF_L need to be constructed for every possible fire breakout location in the building. Focusing on one compartment, Monte Carlo Simulations (MCS) are used to generate the pdf of demand and capacity relative to a given damage state. For steel structures, the random variable representing demand is the maximum temperature in the steel section, whereas capacity is the critical temperature relative to the given damage state (i.e. temperature at failure). Evaluation of the demand should be completed for several (discrete) values of the IM. In this work, the IM for fire hazard is selected as the fire load in the compartment, q in MJ/m². Using the results of the MCS, the complementary cdf of demand $F_D(T, q_i)$ is convolved with the pdf of capacity $f_C(T)$. This yields the probability of failure $P_{F|Hfi}(q_i)$, conditional to the occurrence of a fire H_{fi} and relative to the fire load q_i, according to *Eq. (1)* in which T is the temperature.

$$P_{F|H_{fi}}(q_i) = \int_0^{\infty} [1 - F_D(T, q_i)]\, f_C(T)\, dT \tag{1}$$

The computation is performed for several levels of fire load q_i in order to get the fragility points $P_{F|Hfi}(q_i)$. Then, a fragility function can be fitted, typically assuming a two-parameter lognormal distribution function according to *Eq. (2)*.

$$FF_L \equiv P_{F|H_{fi}}(q) = \Phi\left[\frac{ln(q/c)}{\zeta}\right] \tag{2}$$

where $\Phi[\cdot]$ is the standardized normal distribution function,
c, ζ are fragility function parameters determined by best fit with the points from *Eq. (1)*.

The function given by *Eq. (2)* is valid for the specific fire breakout location (i.e. compartment) that was considered in the analysis. The analysis needs to be repeated for every possible fire location in the building, resulting in as many functions as there are fire compartments.

2.3 Fire fragility function for the entire building - FF_B

The objective is to characterize the overall vulnerability of the building by a single function, without the need to predict where the fire will break out, but considering the different possibilities and associated vulnerabilities in a probabilistic way. This can be done by combining the local fragility functions FF_L into a building fragility function FF_B. This combination takes into account the conditional probability associated with each FF_L (i.e. the probability to have the fire in the corresponding compartment, should a fire occur in the building) by weighting the importance of the FF_L in the global function FF_B. The statistical method explained in [7] is adopted here and is discussed in detail in [5]. As a result, the FF_B has the same mathematical expression as given by *Eq. (2)*, but in which the parameters c and ζ are “weighted combinations” of the parameters of the FF_L.

2.4 Probability distribution of the intensity measure

Fragility functions relate the conditional probability of failure to the hazard IM, i.e. the fire load, see *Eq. (2)*. It is possible to gather statistics about the IM and to adopt a probability distribution. For fire load, Gumbel type distributions are reported in the literature as a function of the building occupancy [8]. Then, the fragility function FF_B can be convolved with this pdf of the fire load f_q (q) in order to yield a single value (scalar) for the conditional probability of failure, see *Eq. (3)*.

$$p_{F|H_{fi}} = \int_0^{\infty} P_{F|H_{fi}}(q)\ f_q(q)\ dq \tag{3}$$

where $p_{F|Hfi}$ is the probability to reach the considered damage state in the building, taking into account the distribution of fire load, conditional to the occurrence of a fire.

2.5 Probability of occurrence of a fire

Beyond the conditional probability of *Eq. (3)*, it is interesting to evaluate the total probability of failure due to fire, which can be done by multiplying $p_{F|Hfi}$ with the probability of occurrence p_{Hfi}, see *Eq. (4)*.

$$p_F = p_{F|H_{fi}} \times p_{H_{fi}} \tag{4}$$

The advantage of the latter formulation is that it accounts not only for the vulnerability given a fire occurs, but also for the propensity to have a fire. Therefore, the effects of active and passive protection measures can be compared using this methodology. Note that, in this work, the considered fires H_{fi} are structurally significant fires, hence fires that could start and grow to become severe.

Different formulations can be chosen for the probability of occurrence of a fire depending on the objectives. For instance, a model has been proposed for predicting ignitions after an earthquake [9]. In the absence of such extreme event, *Eq. (5)* can be used to estimate the annual probability of occurrence of a structurally significant fire in the building with a total floor area of A_{fi} (m^2).

$$p_{H_{fi}} = p_{1,EN} \times p_{2,EN} \times p_{3,EN} \times p_{4,EN} \times A_{fi} \tag{5}$$

where the coefficients $p_{1,EN}$ to $p_{4,EN}$ account for the type of occupancy and the active fire protection measures.

3 ANALYSIS OF MULTI-STORY STEEL BUILDINGS

3.1 Building design

The methodology described in Section 2 is applied on multi-story steel frame buildings. Buildings with variable heights (3, 6, 9 and 12 stories), occupancy and fire resistance rating are considered to allow comparing the fire risk. All buildings have a similar 45.72 m by 45.72 m plan area, consisting of five bays in both directions (*Fig. 2*), composed of four moment resisting frames on the perimeter and interior gravity frames. The columns of the interior frames are continuous but the beams have pinned connections (statically determinate beams). Current American prescriptions were followed for the design. The column sections range from W14x43 to W14x145 and are protected with a dry mix CAFCO Blaze-Shield II from Isolatek. More information is given in [10].

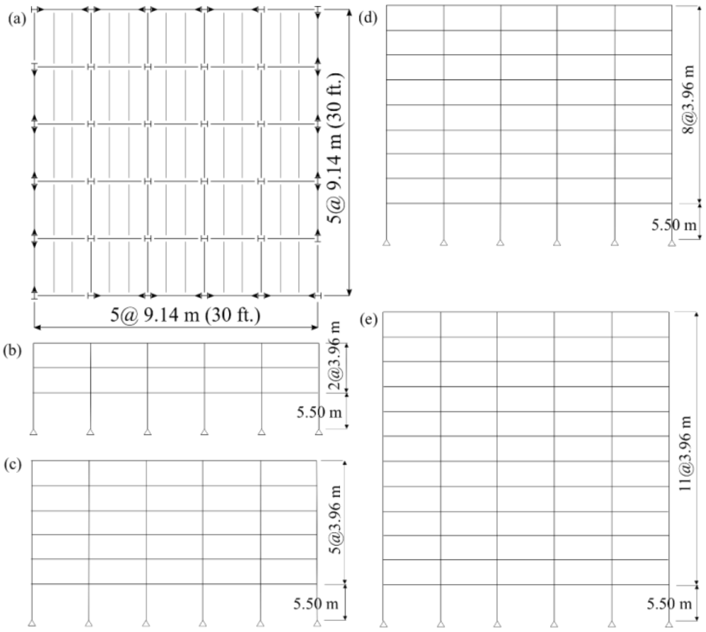

Fig. 2. Steel gravity frames (a) plan and elevation of (b) 3-story, (c) 6-story, (d) 9-story, (e) 12-story

3.2 Considered damage state (i.e. “failure”)

Fire can lead to various degrees of damage in buildings. Damage states (DS) can be defined for estimating the magnitude of the damage, and grouped in categories such as ‘slight’, ‘moderate’, ‘extensive’, and ‘complete’. Examples of DS include compromised non-structural fire safety systems, excessive deflection, or failure of a structural element. A fragility function is derived for each DS, to quantify the probability of exceeding such DS. This study focuses on a single damage state, i.e. the failure of a frame column.

3.3 Models for Monte Carlo simulations

To build the fragility functions, the probability of failure of a frame column in the buildings needs to be estimated. The process relies on the probabilistic assessment of the fire development, the thermal (heat transfer) response and the structural response of the column. The following models are adopted and used in MCS:

- *Fire model*

The Eurocode parametric fire model is used to estimate the gas temperature evolution in the fire compartment. The compartment size and opening factor are selected as random parameters. The compartment size varies between 5 to 10 m in length, 3 to 8 m in width, and 2.5 to 3.2 m in height. All dimensions are assumed to follow a uniform distribution within the given interval. The openings size varies between 1.6 to 3.3 m in width and 1.3 to 1.7 m in height. The JCSS model is then applied for the evaluation of the opening factor as a random quantity [11]. It is assumed that the fire remains contained in the compartment where it started. Since the fire load is the intensity measure, the analyses are conducted for several levels of fire load successively fixed between 100 and 2000 MJ/m², to cover the range of realistic fire loads in a building compartment.

- *Thermal model*

For heat transfer analysis, the finite difference formula of Eurocode 3 is adopted [12]. This formula yields the uniform temperature in the cross-section of a steel member at each time step and it can be used for insulated and bare steel members. This formula is used to get the maximum temperature reached in the column section during the course of the natural fire, which is the demand placed on the member (see $F_D(T, q_i)$ in *Eq. (1)*). The thickness and thermal conductivity of fire protection material are considered as random. A lognormal distribution with a COV of 0.2 is assumed for the thickness of fireproofing, whereas for conductivity, the probabilistic model is based on experimental data and a Bayesian procedure as discussed in [1].

- *Structural model*

For structural response, the simple calculation model prescribed in Eurocode 3 is used [12]. This model allows calculating the design buckling resistance of a compression member with uniform temperature based on conservative assumptions. The moment of inertia corresponding to the member’s weak axis is selected. Knowing the axial load on the column, the model yields the critical temperature at which failure is reached (see $f_C(T)$ in *Eq. (1)*). Selection of a simplified model over a more sophisticated approach is motivated by the need to run a large number of realizations for obtaining the pdf of capacity. The validity of this approach for the studied prototypes has been verified by comparing a selected number of realizations with results of nonlinear finite element simulations. Randomness in steel mechanical properties at elevated temperature is taken into account using the models developed in [1]. The applied gravity loads are also considered as random by adopting the distribution proposed in [13].

4 RESULTS

4.1 Local fragility functions

MCS are run to assess the probability of failure of the columns according to *Eq. (1)*, then the FF_L are constructed using *Eq. (2)*. One FF_L is derived for each possible fire breakout location (i.e.

compartment) in the building. Comparing these FF_L allows analysing the influence of the compartment where fire occurs on the vulnerability of the frame columns. *Fig. 3a* shows a sample of results for the prototype building with 12 story, a 2-hour fire protection rating and columns exposed to fire on 3 sides along the strong axis. The fragility functions at different floors are similar to each other indicating a similar vulnerability to fire. In the design, the utilization ratio of columns along the height is optimized and approximately kept constant to obtain a similar safety level at each story. Yet, when the same column section is used on two stories (column splices are located at every two story), the lower story is more vulnerable than the upper because of larger gravity loads on the lower story. Furthermore, the column of the first story is the most vulnerable because of a higher slenderness ratio (larger story height and pinned boundary condition at the base while intermediate stories have rotational stiffness on both ends).

In conclusion, a risk analysis based on the FF_L is useful to highlight vulnerable compartments in a building. However, it does not account for the effects on the risk of the total number of compartment (it is local), the likely value of the fire load (it is function of the IM) or the probability of occurrence of a fire (it is conditional).

4.2 Building fragility functions

Next, building fragility functions FF_B are constructed from the combination of the FF_L. A single FF_B is obtained for each type of building, i.e. building with a certain number of story (3, 6, 9 or 12), fire protection rating (0, 1, 2 or 3 hour) and number of fire exposed faces for the columns (3 or 4). *Fig. 3b* shows results for buildings with columns exposed to fire on 3 sides along the strong axis. The fire rating influences a lot the building fragility functions. However, the number of story does not have any significant influence. When the number of story increases, the probability to have a fire increases, but the conditional probability of failure should a fire start is virtually unchanged. For the considered prototype buildings, the fire rating requirement for the frame columns is typically 2h (except for the 12-story which is 3h). According to the obtained results, this requirement allows to reach low probability of failure for typical values of the fire load (in the range 300-800 MJ/m^2).

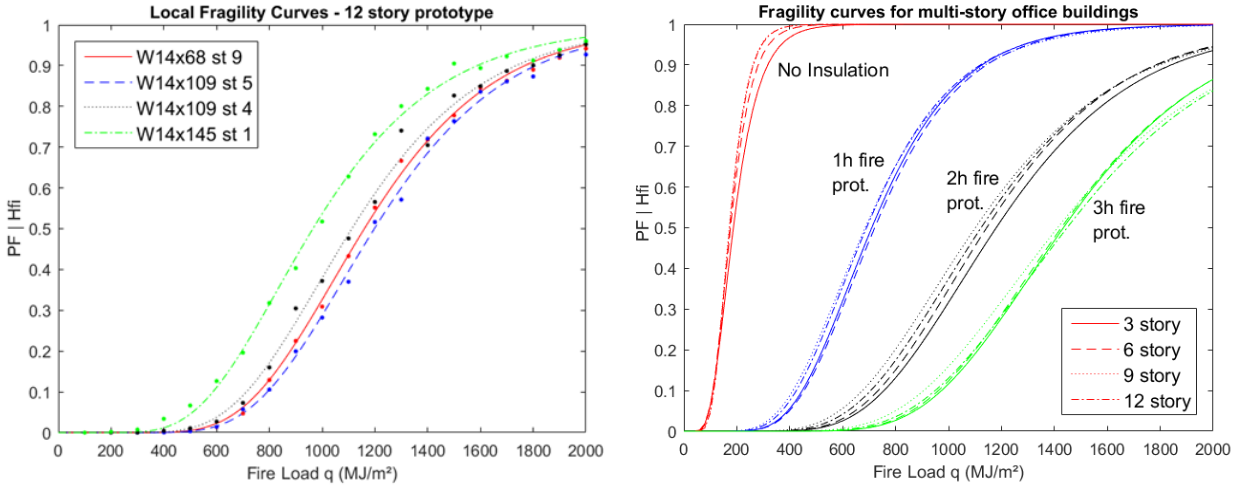

Fig. 3. a) FF_L for different columns of the prototype 12-story building with 2-hour fire protection;
b) FF_B for the prototype buildings with different number of story and fire protection rating.

The influence of building occupancy was also investigated and it was found that it hardly affects the fragility. Similar to the number of story, the occupancy influences the probability to have a fire, but it does not influence the vulnerability of the structure once a fire has started and grown.

In conclusion, a risk analysis based on the FF_B allows comparing the vulnerability to fire of different buildings, taking into account the entire structure. Yet it still does not incorporate the likely value of the fire load or the probability of occurrence of a fire.

4.3 Probability of column failure due to fire in the building

In this section, the total probability of failure is evaluated for buildings of 3, 6, 9 and 12 stories, with different occupancies consisting of office, dwelling or library. The fire protection rating considered here is in accordance with the code, i.e. a 2-hour rating for the 3, 6 and 9 story buildings and a 3-hour rating for the 12 story buildings.

– *Fragility functions FF_B*

The parameters [c (in MJ/m²), ζ] of the FF_B for the buildings with 3, 6, 9 and 12 stories are equal to [1180, 0.347], [1144, 0.346], [1101, 0.382], and [1448, 0.329] respectively. The 12 story building has a lower vulnerability compared with the others (higher value of c), due to its higher fire protection rating (see *Fig. 3b*). As discussed above, the FF_B do not depend on the occupancy.

– *Probability distribution of the fire load q*

Statistics are reported in the literature for the fire load as a function of the building occupancy. Here, Gumbel type distributions are adopted with a mean (in MJ/m²) and standard distribution for office, dwelling and library occupancy type equal to [420, 126], [780, 234], and [1500, 450] respectively. By convolution of the distributions for q with the FF_B (see *Eq. (3)*), one obtains the conditional probability of failure of a column in the building in case of fire $p_{F|Hfi}$. The results are plotted in *Fig. 4a*. The library is the most vulnerable in case of fire due to the higher fire load.

– *Probability of occurrence of a fire*

The probability of occurrence of a fire p_{Hfi} is calculated with *Eq. (5),* which depends on the occupancy and on the total floor area (correlated with the number of stories). For the 3 story building, the probability of occurrence is equal to 2.4×10^{-7} (office and library) or 5.1×10^{-7} (dwelling) per year. This increases proportionally with the number of stories, see *Fig. 4b*.

– *Annual probability of fire-related failure of a column in the building*

Finally, *Eq. (4)* is used to calculate the total probability of failure (per year). The results are plotted in *Fig. 4c*. The values range from 0.007×10^{-7} per year for the 3-story office building to 3.795×10^{-7} per year for the 9-story library. The office buildings, having the lowest fire load and the lowest probability of occurrence of a fire, have a very low probability to experience a column failure.

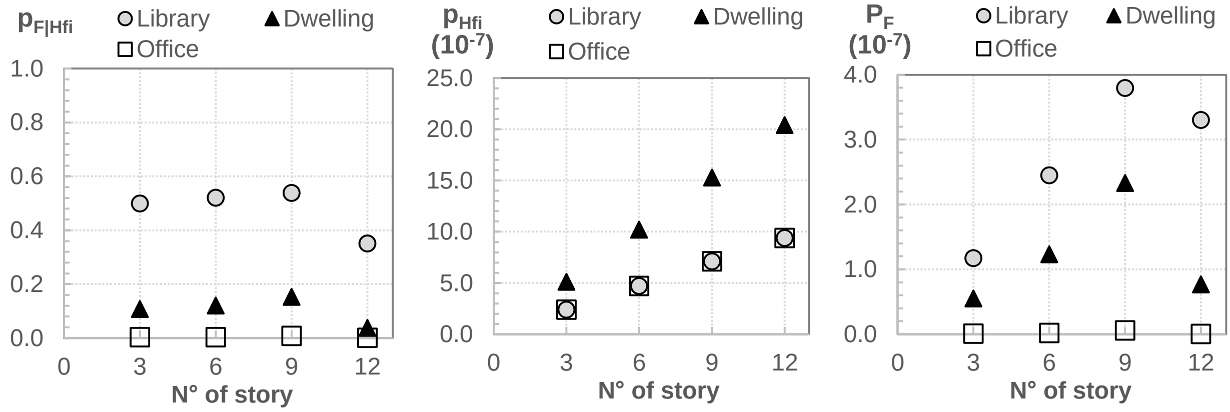

Fig. 4. a) Conditional probability of failure of a column in the building in case of fire $p_{F|Hfi}$;
b) probability of occurrence of a fire in the building p_{Hfi};
c) total (annual) probability of failure of a column in the building due to fire.

The probability of failure increases significantly when the number of story increases from 3 to 9. Indeed, the prescriptive requirements are the same for these buildings (2-hour fire protection rating on the elements), based on a safety target at the element level. However, this disregards the fact that the number of elements in the system (i.e. the number of columns in the buildings) will influence the probability to have a failure somewhere in the building. In a full probabilistic analysis, it is possible to apply the target value to the “aggregate” reliability of the system rather than to the reliability of the individual elements. Note that the fact that the prescriptive requirements are more severe for taller buildings (for example the 12 story in this study) allows indirectly to take the system behaviour into account, in a first step toward a consistent safety level between buildings.

5 CONCLUSIONS

This paper describes a methodology to assess the risk of structural failure due to fire for multi-story buildings, based on the use of fragility functions and a full probabilistic approach. The methodology has four steps: (i) constructing local fragility functions for fire scenarios in individual compartments; (ii) combining the latter into building fragility functions for the overall vulnerability to fire; (iii) adopting a probability distribution for the fire load (IM) in the building to obtain a unique value for the conditional probability of failure; and (iv) multiplying with the probability to have a fire in the building. The following main conclusions can be drawn:

- The methodology incorporates in a unique framework the uncertainties in fire occurrence and location, fire development, heat transfer processes and structural response, at the building scale.
- The use of fragility functions allows separating the evaluation of the fire occurrence likelihood and intensity of the fire, from the conditional vulnerability of the structure. This notably allows treating separately the effects of active fire protection measures and passive fire protection.
- The building height and occupancy do not influence the fire fragility, but they influence the total reliability because they affect the distribution of fire load and the probability to have a fire.
- The prescriptive approach, which requires the same level of hourly rating for a given element in a building, does not provide the same level of safety in buildings of different heights.

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