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Critical parameters in deriving fire fragility functions for steel gravity frames

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ABSTRACT

Fire fragility functions can be used to characterize the probabilistic vulnerability of buildings to fire in the context of urban resilience assessment. A methodology has been proposed to develop such functions for multi-story steel buildings. However, a large number of parameters with uncertainties play a role in the process of constructing the fragility functions. The goal of this research is to identify the critical parameters that most affect the global fire safety by investigating the sensitivity of the fragility functions to different input parameters. Sensitivity in parameters affecting the fire model, the heat transfer process and the thermo-mechanical response is examined. The effects of different design assumptions at the system level are also studied. The presented approach is useful for selecting the prevailing parameters in a fire reliability analysis and it provides important information for modeling tools that can be used to evaluate resilience for fire scenarios.

INTRODUCTION

The standard approach in fire design of structures is mainly based on design at the component level using prescriptive approaches, where uncertainties in variables are not explicitly incorporated in the process. However, measured data indicate large uncertainty in the values of the parameters affecting the fire behavior of structures, including for instance fire load and material properties at elevated temperatures. An appealing way to measure these uncertainties is to develop fragility functions.

Fragility functions provide the probability of exceeding a damage state (e.g. column failure, excessive beam deflection, connection failure, etc.) for a given intensity measure of the hazard (fire in this case). The damage states are generally related to the structural performance level and can be grouped in different categories such as ‘no damage’, ‘slight’, ‘moderate’, ‘extensive’, and ‘complete’.

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Fragility functions can be used for evaluating losses at the scale of a community in the context of disaster resilience assessment [1].

In the seismic engineering field, the approach of using fragility functions has been largely adopted. The scientific community has developed a suite of seismic fragility functions for different structural typologies, e.g. [2]. The method generally consists of deriving analytical fragility functions based on stochastic analyses of prototype buildings that are assumed to be representative of a typology. The parameters in the analyses are assumed to be random variables and Monte Carlo Simulations (MCS) are used to generate the distributions. Alternatively, empirical functions can be developed when sufficient historical damage data is available [3].

In this context, the present research aims at developing a framework for constructing fire fragility functions. Over the past years, research in fire engineering has started to progress toward the development of a performance-based framework that explicitly accounts for uncertainties. Contributions notably include the work by Lange et al. to establish a methodology for performance-based fire engineering of structures based on the seismic engineering framework developed in the Pacific Earthquake Engineering Research (PEER) Center [4]. However, the development of fire fragility functions in a system level approach to quantify structural vulnerability has not been addressed yet.

In a previous study [5], the authors developed a novel methodology to generate fire fragility functions, which measure the performance of an entire building system (rather than a single component). The fragility functions can be used to evaluate a city’s resilience to fire hazard, including in case of multi-hazard cascading event such as fire following earthquake. However, the process of generating these fire fragility functions raises several important questions. The computational time for thousands of simulations (required by MCS) to model the performance of a building system under fire can be excessive. The large number of input parameters with uncertainty adds to the complexity of analysis and the computational time. For these parameters, probability distributions need to be assumed but rigorous data are often lacking. In order to prioritize the efforts in data collection and limit the complexity of the analyses, it is crucial to identify the parameters that most affect the global fire safety. Furthermore, the sensitivity of the results to different input parameters and assumptions should be quantified. Addressing these issues, this paper aims at identifying the most important input parameters, based on sensitivity analyses, to be considered as random variables when developing fire fragility functions for entire buildings.

METHODOLOGY

Fire Fragility Functions

The methodology for developing the fire fragility functions has been presented in detail in [5]. It requires the probabilistic assessment of the structural system performance under fire. This assessment takes into account uncertainties in the fire model, the heat transfer model and the structural response, in addition to fire scenarios at different locations in the building. The intensity measure selected as the control parameter to characterize the hazard is the fire load. For a given fire load q, MCS can be used to generate the probability density function (PDF) of demand and capacity relative to a given damage state. Convolution of the complementary cumulative distribution function (CDF) of demand $F_{D|q}(\cdot)$ with the PDF of capacity $f_C(\cdot)$ yields the probability of reaching the damage state $P_{F|q}$, according to Eq. 1.

$$P_{F|q} = \int_0^\infty \left[1 - F_{D|q}(T)\right] f_C(T)\,dT \tag{1}$$

The computation is performed for several levels of fire load in order to get the fragility points. Then, a fragility function can be fitted, typically assuming a two-parameter lognormal distribution function.

In this procedure, the random variable representing demand is the maximum temperature in the steel section (for a given fire load). Capacity is the critical temperature in the steel section relative to the given damage state (i.e. temperature at failure). The PDF obtained for demand and capacity are key for constructing the fragility functions. However, these PDF depend on the input parameters and modeling assumptions.

The fragility functions are first built at the component level, assuming a fire scenario in a well-defined compartment. These are referred to as local fragility functions (FFL). Then, building fragility functions (FFB) are built from the combination of the FFL for characterizing the overall vulnerability of the building [5]. In this second step, parameters at the system level may also influence the fire fragility functions (e.g. number of stories).

Building Prototype

For the sensitivity analysis, this paper focuses on a specific typology, namely a multi-story steel frame building. Similarly, a single damage state is considered, i.e. the failure of a frame column. The presented approach can be applied to other building typologies and damage states.

The considered building prototypes consist of steel structures with variable heights, designed based on the FEMA/SAC project for the Los Angeles area. Four prototype buildings are considered with 3, 6, 9, and 12 stories. The four prototype buildings have a similar 45.72 m by 45.72 m plan area, consisting of five bays in both directions (Figure 1). Each structure is 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). The work focuses on the vulnerability to fire for columns in an interior frame.

Analytical modeling for probabilistic assessment

This section describes the models that are used to assess the probabilistic fire performance of the building structure. The models are used in MCS for constructing the fire fragility functions. The input parameters in these models that are considered as random are discussed in the next section.

The Eurocode parametric fire model [6] is used to estimate the gas temperature evolution in the fire compartment. The nominal fire compartmentation of the buildings under study is based on a subdivision in compartments of 9.144 m long and 6.096 m wide. It is assumed that the fire remains contained in the compartment where it started.

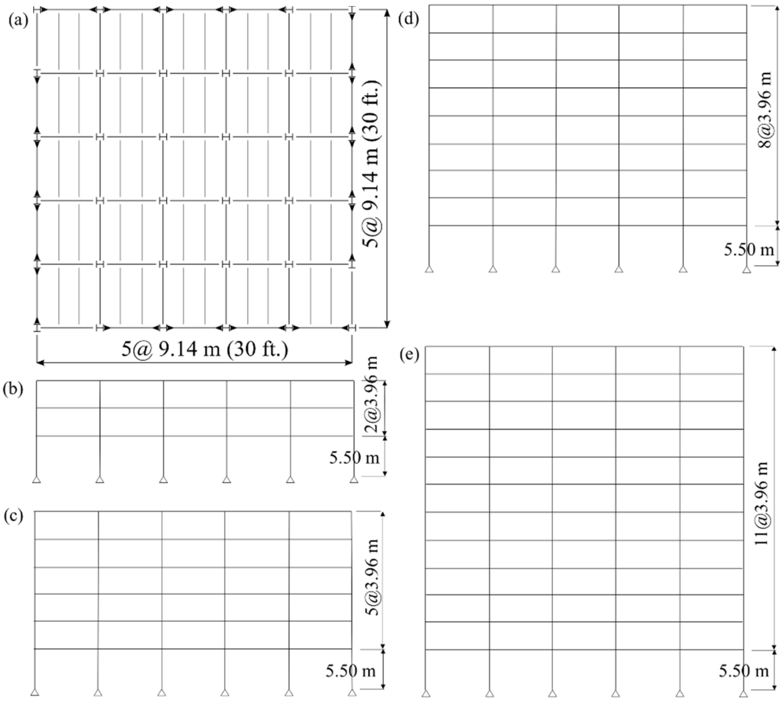

Figure 1. Steel gravity frames (a) plan and elevation of (b) 3-story, (c) 6-story, (d) 9-story, (e) 12-story

Gypsum plasterboard is assumed as the lining material for walls and ceiling of the prototype building.

For heat transfer analysis, the finite difference formula of Eurocode 3 is adopted [7]. This formula, also referred to as lumped mass approach, 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 section during the course of the natural fire; this maximum temperature is the demand placed on the member (see Eq. 1).

For structural response, the simple calculation model prescribed in Eurocode 3 is used [7]. This model allows one to calculate 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. Selection of a simplified model over a more sophisticated approach (e.g. nonlinear finite element modeling) is motivated by the need to run a large number of realizations for obtaining the PDF of capacity. For the studied prototype, the gravity frame columns are mainly subjected to compression with minor moment, because of the pinned connection with the beams. While thermal gradients create bending in the columns when heated on three faces, this effect does not affect significantly the critical temperature (for the prototype studied here). This has been verified by comparing a selected number of realizations with results of nonlinear finite element simulations.

Parameters with Uncertainty

The parameters with uncertainty considered in the study are listed in Table I. These parameters have been selected because they are expected to be the most significant sources of uncertainties based on literature and engineering judgment. Table I includes parameters affecting the demand and capacity at the component level, as well as different configurations at the system (building) level. Yet this list is not exhaustive and will be completed in further analyses.

TABLE I. LIST OF PARAMETERS WITH UNCERTAINTY

Fire Fragility Local (FFL): component level		**Fire Fragility Building (FFB): system level**
Demand	**Capacity**	
Compartment geometry	Mechanical properties of steel	Fire resistance rating
Opening factor	Dead load	Fire exposed faces
Thermal conductivity of fireproofing	Live load	Building height
Thickness of fireproofing		Building occupancy

On the demand side, uncertainties in the following parameters of the fire model are considered: compartment geometry and opening factor. Fire load is also a varying parameter but it is a case apart as it is used as the intensity measure for fragility functions. The probabilistic model for thermal conductivity of fireproofing at elevated temperatures is based on experimental data and a Bayesian procedure [8]. A lognormal distribution is assumed for the thickness of fireproofing. On the capacity side, randomness in the mechanical properties of steel and in the applied gravity loads is considered.

At the system level, different fire resistance ratings are considered, which translates into different insulation thicknesses. The ratings range from no insulation to 3-hour fire resistance insulation based on prescriptive design. Note that the case with no insulation is potentially relevant in a cascading multi-hazard scenario, e.g. after an earthquake that would damage the insulation. Different configurations in terms of cross-section fire exposure are analyzed: three sides along the weak or strong axis, or four sides. The considered four building heights allow to span the different classifications (low, medium, and high-rise) based on Building Structure Categories for steel frames defined in Hazus [9]. Finally, the influence of different building occupancy is studied, e.g. re-assigning two stories as dwellings instead of offices.

RESULTS OF SENSITIVITY ANALYSIS

At the Component Level

For a fire in a given compartment, local fragility functions (FFL) are constructed to provide the probability of reaching the column failure as a function of the fire load. The objective is to identify the parameters that must necessarily be considered as random when constructing the FFL. This is done by analyzing the sensitivity of demand and capacity PDF’s to the different input parameters.

For the sensitivity analysis, MCS are conducted using mean values for all input parameters except the one for which the values are selected randomly based on its probability distribution. This allows to isolate the effect of the variance of each input parameter on the variance in the output.

On the demand side, the output is the maximum temperature reached in the column section. Figure 2 shows a sample of results for a column section W14x68 protected with a prescriptive 2-hour fire rating. The plots show the mean, plus and minus one standard deviation, of the maximum steel temperature for different selected random parameters. The results are given for fire loads equal to 600 MJ/m² and 900 MJ/m². Each case is based on 200 simulations. The two values of mean and standard deviation provide a reasonable measure of uncertainty since the results follow a normal distribution. The parameters 'compartment geometry' and 'opening factor' influence the fire model, whereas the parameters related to fireproofing influence the heat transfer model. Figure 2 shows that uncertainties in both the fire model and the heat transfer model cause significant variance in demand. The opening factor is the parameter that least influences the demand, yet its influence is not negligible.

On the capacity side, the output is the critical temperature at which the column fails. Figure 3 shows a sample of results for a column section W14x68. The column capacity does not depend on the characteristics of the fire (such as the fire load). However, it depends on the story level, because the story influences the load on the column. The results are given for columns at the fifth and sixth story of the nine-story building. The randomness in steel mechanical properties at elevated temperature contributes the most to the variance of the capacity. In contrast, the influence of live load is negligible. For the studied prototype, live load could be considered as deterministic.

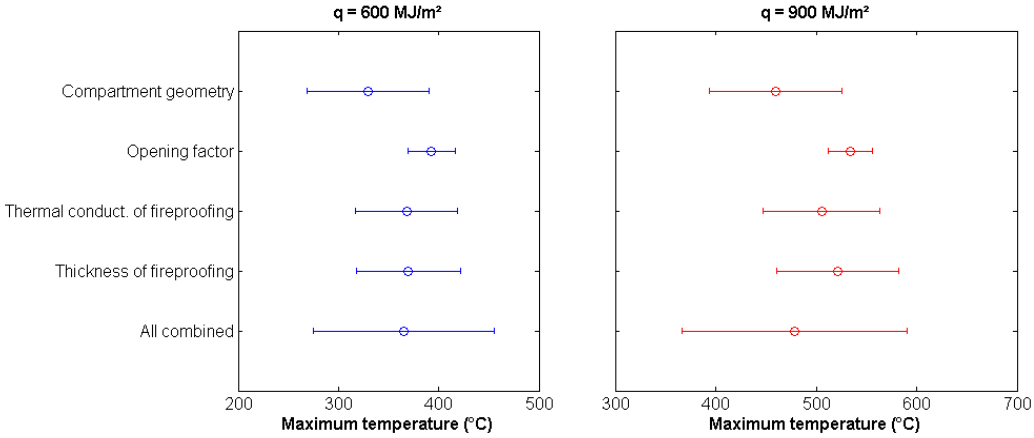

Figure 2. Sensitivity of maximum steel temperature to demand parameters for a W14x68 section.

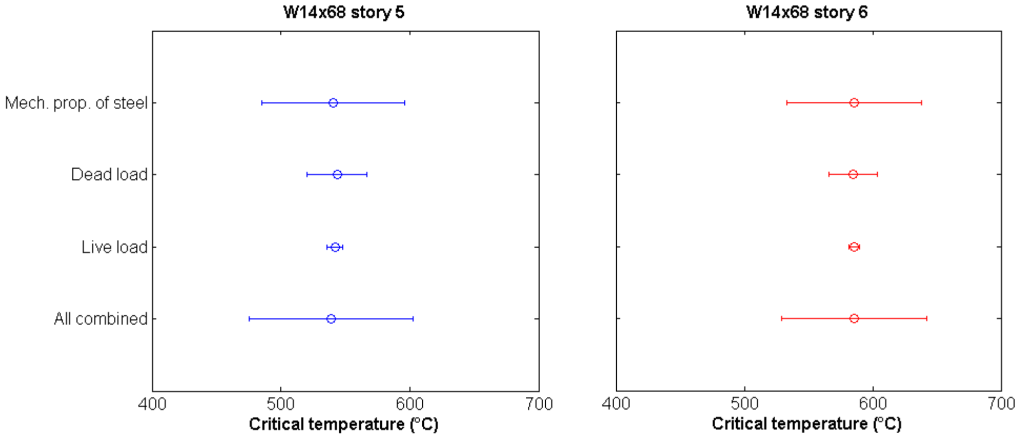

Figure 3. Sensitivity of steel temperature at failure to capacity parameters for a W14x68 section.

At the System Level

At the system level, the FFL constructed for each different compartment fire locations in the building are combined to obtain the building fragility functions (FFB) representative of the vulnerability of the entire building. At this scale, the objective is to investigate the sensitivity of the FFB to different design assumptions for the prototype building. This allows one to discuss the effects of various parameters on the global fire safety of the building.

In constructing the fragility functions, all parameters listed in Table I at the component level are assumed as probabilistic. The functions are successively built for different values of the system level parameters (e.g. for different building heights).

Figure 4 shows a sample of results. Fig. 4a shows that the number (3 or 4 sided fire) and orientation of fire-exposed faces (along weak or strong axis) of the columns influences the fragility curve of the building for column damage state. The building is more vulnerable if the columns are exposed on four faces than on three faces, because of the faster temperature increase that the former generates. Note that the results are given for a fireproofing thickness design independent of the number of fire-exposed faces (for instance the compartmentation layout may vary during the lifetime of the building, without retrofit of the fireproofing). Interestingly, Fig. 4a shows that a building whose columns are exposed on four faces needs a 3h fireproof rating to reach the same reliability level as a building with a 2h fireproof rating whose columns are exposed on three faces along the weak axis. Hence, the fire safety can be improved by reducing the number of fire exposed faces of columns, as an alternative to adding more fire protection.

Fig. 4b shows that the fire rating influences the building fragility curves. However, the building height does not have any significant influence. It should be noted that when the height of a building increases, the probability to have a fire ignition increases, but the conditional vulnerability should a fire start is approximately unchanged. For the considered prototype building, the fire rating requirement for the frame columns is typically 2h (it is 3h for the 12-story building). 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/m²).

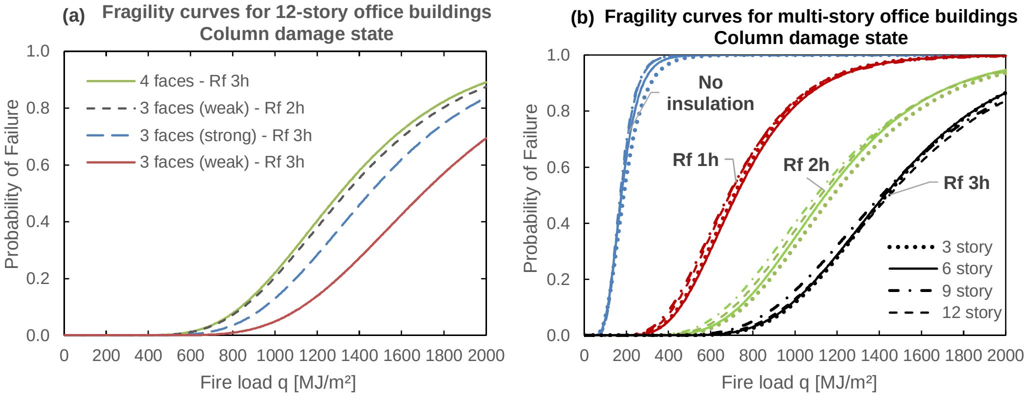

Figure 4. Sensitivity of fire fragility curves to (a) fire exposed faces of column (b) fire resistance rating and building height.

The building occupancy influences the probability of fire occurrence. This has no effect on the FFB when the occupancy is homogeneous in the building, because FFB gives conditional probabilities. Hence, changing the occupancy of a whole building from offices to dwellings does not affect at all the fragility functions of this building. However, the occupancy may affect the FFB when a different occupancy is assigned to part of the building only. In that case, the relative likelihood of a fire event is modified in that part of the building. This leads to assigning different weights to some of the FFL in the process of constructing combined functions. If a part of the structure is particularly vulnerable and its occupancy is such that the relative likelihood of a fire event in this part increases, then the overall vulnerability of the building to fire increases as well.

CONCLUSION

The sensitivity of fire fragility functions is quantified with regards to the effects of the uncertainties in the prevailing parameters. The presented approach allows one to evaluate which parameters should consider randomness and which could be assumed as deterministic. This approach is important in order to prioritize the efforts in data collection and limit the complexity of the probabilistic analyses. The obtained results have implications for modeling tools that can be used to evaluate community resilience for fire scenarios.

The study focuses on a specific building typology consisting in a multi-story steel frame structure. Fire fragility functions should be developed for other building typologies and similar sensitivity analyses should be conducted to identify the parameters that affect global fire safety for these different typologies.

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