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Fire fragility curves for steel buildings in a community context: A methodology

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This paper proposes a novel methodology for developing fire fragility functions for an entire steel building – meaning that the function is not specific to a location within the building. The aim is to characterize the probabilistic vulnerability of steel buildings to fire in the context of community resilience assessment. In developing the fragility functions, uncertainties in the fire model, the heat transfer model and the thermo-mechanical response are considered. In addition several fire scenarios at different locations in the building are studied. Monte Carlo Simulations and Latin Hypercube Sampling are used to generate the probability distributions of demand placed on the members and structural capacity relative to selected damage thresholds. By assessing demand and capacity in the temperature domain, the thermal and the structural problems can be treated separately to improve the efficiency of the probabilistic analysis. After the probability distributions are obtained for demand and capacity, the fragility functions can be obtained by convolution of the distributions. Finally, event tree analysis is used to combine the functions associated with fire scenarios in different building locations. The developed fire fragility functions yield the probability of exceedance of predefined damage states as a function of the fire load in the building. The methodology is illustrated on an example consisting in a prototype nine-story steel building based on the SAC project.

1. Introduction

In recent years, the methods for analyzing structures in fire have moved toward a probabilistic framework. This framework explicitly recognizes the role of uncertainty in the evaluation of the response of structural systems to fire exposure. Hence, it provides valuable information about the reliability of structural systems, which is not accessible with deterministic methods. The reliability of structures in fire is an essential component of a safer and more resilient built environment.

In this shift toward probabilistic analysis, research efforts have notably focused on developing probabilistic models for the fire engineering parameters with significant uncertainty. Iqbal et al. computed the statistical parameters based on raw experimental data for parameters such as the compartment characteristics and thermal properties of fire protection material [1]. Elhami Khorasani et al. conducted an extensive survey data on fire load density in office buildings and proposed a probabilistic model based on a Bayesian approach [2]. Statistics have also been reported for the mechanical loads [3,4] and for the evolution of the mechanical properties of steel with temperature [5]. Additionally, research has progressed toward providing the probabilistic methods to account for these uncertainties in fire engineering. Lange et al. [6] established a methodology for performance-based fire engineering of structures based on the performance-based earthquake engineering framework developed in the Pacific Earthquake Engineering Research (PEER) Center. Nigro et al. conducted a probabilistic plastic limit analysis of a steel-braced parking structure using Monte Carlo simulation [7]. Guo and Jeffers [8] provided a comparison between the first/second order reliability methods and Monte Carlo approach for the reliability analysis of a protected steel member in fire. The methods proposed so far have mainly focused on the fire reliability of isolated structural members rather than structural systems [9–12]. Additional research is needed to develop a more comprehensive framework that incorporates the uncertainties in fire scenario, heat transfer processes and thermo-mechanical response in a global methodology at the building scale.

In seismic engineering, the research community has developed a probabilistic framework to evaluate the vulnerability of the built environment to earthquake hazard. In order to assess the damage

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loss in a community of buildings subjected to a given earthquake, fragility functions have been developed for the different typologies of structures, e.g. [13–15]. These functions relate the probability of exceeding certain levels of damage in a structure with the intensity of the hazard affecting the structure. They incorporate the uncertainties on the demand and the capacity affecting the structural response. For an earthquake, the hazard intensity for a building can be measured by, for instance, the peak ground acceleration or spectral displacement.

In fire engineering, the only research works focused on fragility functions, to the authors' knowledge, are due to Vaidogas et al., who developed fragility functions for timber members in fire with the char depth as the intensity measure [16]. The framework established by Lange et al. [6] for performance-based fire engineering, based on the PEER methodology, uses fragility functions in order to estimate the damage measures based on the engineering demand parameters. The pioneering contribution of Lange et al. addresses important questions such as the selection of the intensity measure and the link between the hazard and the structural domains, which provides insight for the present research. The difference in approach between the former contributions and the authors' is that the former use fragility functions at the member level while the authors use the fragility functions in a system level approach to quantify vulnerability of a structure.

Fragility functions offer a comprehensive method for characterizing the vulnerability of structures to specific hazards, while incorporating explicitly the effects of uncertainties. The fragility functions can be plotted to convey visually the effects of the uncertain parameters on the vulnerability; the graphs of the functions are referred to as fragility curves. Hence, this method is convenient for conducting sensitivity analyses or comparing different typologies of structures as regards the vulnerability to fire. Additionally, this approach is well adapted to the issue of community resilience against man-made or natural hazards. The latter reason explains the popularity of this approach in seismic engineering. Yet, the concern about the resilience of a community of buildings extends to fire hazard. For instance, conflagrations affecting a community may occur following a major earthquake, as highlighted by past events such as the Loma Prieta earthquake in 1989 [17,18]. In this case, fire fragility functions are needed for the different typologies of buildings in the community to evaluate the damage loss due to fire.

In future, fire fragility functions could be used as a tool for evaluating a city's resilience to fire hazard. The functions are intended to be incorporated into a broader framework in conjunction with Geographic Information System (GIS) software. For instance, the software HAZUS developed by FEMA incorporates seismic fragility functions; it could be enriched with fire fragility functions. In this framework, the functions could be used in conjunction with data on infrastructure and the built environment as well as probabilistic models for the occurrence and spatial distribution of ignitions. By combining the probability of occurrence of fire with the fire fragility functions, the user could estimate the structural damage within a community. Possible applications include the prediction of the extent of probable losses due to fire within a certain time frame (e.g. per year) or following a specific event such as an earthquake or an explosion in an industrial area. Such probabilistic predictions will provide input for risk-informed decision making at the scale of a community.

Based on these considerations, this research proposes a methodology for developing fire fragility functions for steel buildings. The contribution of this work is twofold. First, the novel methodology provides a comprehensive framework for probabilistic fire analysis, by addressing the different sources of uncertainties (fire scenario, heat transfer processes, thermo-mechanical response) at the level of the structural system (the entire building). Second, fire fragility functions developed following this methodology could be used in the probabilistic assessment of a community response to a fire hazard. In future research, fire fragility functions will be derived and implemented into a GIS based risk assessment software platform. Using such a platform, one will then be able to assess the expected risk and cost associated with fire events (e.g., fire following earthquake) for a community of buildings.

The general procedure for the development of fire fragility functions for community resilience assessment is illustrated in Fig. 1.

The procedure in Fig. 1 deals with different scales. At the local scale, the local fragility functions, FF_L, are derived considering that the fire develops in a well-defined compartment of the building. These fragility functions will generally be different for each fire location within a same building, i.e., $FF_{L,i} \neq FF_{L,j}$. In this work, it is assumed that the fire remains contained within one compartment. The possibility of fire spread beyond a compartment will be addressed in future works. At the scale of the building, the many local fragility functions (corresponding to each fire location) must be combined in order to yield the building fragility functions, FF_B. The latter characterize the overall vulnerability of the building to fire. Finally, at the scale of the community, these building fragility functions are mapped to the buildings of the same typology. Other typologies of buildings need their own fragility functions. Hence, the resilience assessment of a community requires the inventory of the buildings in this community with their typologies (structural types) and the fragility functions $FF_{B,k}$ associated to each typology. The methodology for generating the fragility functions at the local scale and at the building scale is described in the next section. The extension at the community level will be addressed in future works. The "Flowchart" described in Fig. 1 refers the reader to flowcharts presented in next sections of this paper.

This paper is structured as follows. Section 2 describes the proposed methodology for developing fire fragility functions. A framework is presented to construct the fragility functions at the scale of a compartment and then to combine them at the scale of a building. Section 3 introduces a prototype building that is used as a worked example. This example is intended for illustration of the methodology and requires the adoption of simplifying assumptions; it should be considered as an introduction to possible future applications. Section 4 discusses the parameters with uncertainty in the worked example. Section 5 addresses the probabilistic assessment of capacity of the structure in fire, whereas Section 6 addresses the probabilistic assessment of the demand placed on the structure. In Section 7, the methodology for constructing the fire fragility functions is applied to the worked example, using the results of Sections 5 and 6. The vulnerability of the prototype building to fire is obtained and the results are discussed. Finally, the conclusions of this research are presented in Section 8.

2. Methodology for developing fire fragility functions

Fire fragility is a conditional probability statement describing the vulnerability of a system subjected to a given fire intensity. When developing fire fragility functions, it is assumed that a fire that is able to endanger the structure has started; such fire is referred to as structurally significant fire in this work. Hence, the factors that influence the probability of a structurally significant fire to happen, such as the presence of fire detection or sprinkler systems, have no effect on the fragility functions.

A methodology for generating analytical fire fragility functions is developed in this paper. For the sake of clarity, the methodology is presented in the framework of a practical example, namely a nine-story steel frame building. The example is intended as an introduction to possible applications, using a series of simplifying