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Framework for a performance-based analysis of fires following earthquakes

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ABSTRACT

Most current structural fire codes focus on achieving prescribed fire ratings, which are based on standard fire tests with minor relevance to what is required for fire safety. These prescriptive design approaches do not provide sufficient information regarding the performance of structural members or systems under elevated temperatures. Furthermore, the limited structural design provisions provide no indication of the level of reliability of structures since comprehensive treatment of the uncertainties associated with the hazard is not considered. It is therefore imperative to move towards performance-based engineering not only to quantify structural reliability for given performance objectives but also to ensure more economic and safe design. This paper provides details on the development of a new analysis framework for probabilistic performance-based analysis of a fire following an earthquake. The framework is then utilized to develop fragilities of steel structural members and systems subjected to cascading hazards of earthquake and fire while considering buckling of columns as the damage limit state. Uncertainties associated with fire hazard, passive fire protection, gravity load, and earthquake intensity are accounted for in the framework. The proposed performance-based approach for the analysis of a fire following an earthquake can be considered an extension of the Pacific Earthquake Engineering Research (PEER) performance-based earthquake engineering framework and used by engineers to assess structural performance under the multiple hazards.

1. Introduction

The majority of fire design approaches for steel structures are based on prescriptive measures, mainly addressing how a building should be protected in a fire event. Performance-based analysis, however, pertains to how a structure should perform to meet fire safety objectives. To date, limited studies have been conducted to probabilistically evaluate the performance of steel members and systems under fire, e.g., [1–7]. For fire following earthquake, probabilistic studies are almost nonexistent except recently published articles [5,8].

In the area of probabilistic fire analysis, a work was conducted by Iqbal and Harichandran [1] who proposed a framework to determine resistance and load factors for fire design of structural members. The study pertained to assessment of the statistical characteristics of the random variables that are relevant in fire design of structural steel members. It was concluded that significant uncertainties exist in fire design parameters of structural members compared to design parameters at ambient temperature. Guo et al. [2] and Guo and Jeffers [3] developed probabilistic frameworks to evaluate the fire resistance of structural members while considering uncertainties associated with fire hazard and structural resistance parameters. Statistical data was specified for random variables and a large set of deterministic thermal-mechanical analyses was conducted. The proposed framework was demonstrated by analyzing a protected steel beam [2] and column [3] to determine probability of failure at a given level of uncertainty in fire. Recent work has been conducted by Lange et al. [4] to establish performance-based structural fire engineering based on extensive work conducted on performance-based earthquake engineering. In their study, hazard, structural system, and loss domains, which are essential features of any performance-based engineering framework, were defined in accordance with structural fire engineering. Khorasani et al. [5] performed probabilistic analysis to determine the level of reliability of structural members under fire through modifying the thermal module of OpenSees [9] to enhance its fire analysis capabilities. In a follow up study, the authors used a Bayesian probability approach to predict the fire load density in office buildings using survey data that they have collected from the literature [6]. The proposed models showed good correlation with available data and provided better fit than those in Eurocode 1 [10] and NFPA 557 [11]. A follow up study was completed by Khorasani et al. [7] on uncertainty modeling of mechanical and thermal properties of structural steel and thermal properties of passive fire protection for probabilistic fire analysis. An illustrative example was performed on a steel column and the results showed that the insulated column is not susceptible to failure under fire.

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Nomenclature

b	thermal absorptivity (J/m^2 s$^{0.5}$ K)
c	specific heat (J/kg C)
c_s	specific heat of steel (J/kg C)
c_p	specific heat of SFRM (J/kg C)
D	information of structure (e.g., location, geometry, loads, design, etc.)
D^*	inner perimeter of fire protection (m)
d_p	fire protection thickness (m)
DM_E	damage measure in the earthquake
DM_{FFE}	damage measure in fire following earthquake
DV_{FFE}	decision variable in fire following earthquake
EDP_E	engineering demand parameter in the earthquake
EDP_F	engineering demand parameter in fire
g	annual rate of an event (hazard)
$g(X)$	damage function
IM_E	intensity measure of the earthquake hazard
IM_F	intensity measure of fire hazard
j	node label in finite difference analysis
k_p	thermal conductivity of SFRM (W/m C)
n	number of time increment in finite difference analysis
N	total number of simulations in MCS
N_f	number of simulation in which the system fails
O	opening factor (m$^{0.5}$)
O_{max}	maximum opening factor (m$^{0.5}$)
$O(*)$	truncated error
p	complementary cumulative distribution function
$P[*]$	cumulative distribution function (CDF)
P_f	probability of failure
$R_f(X)$	column capacity (kN)
$S_f(X)$	column demand (kN)
t	time (s)
T_f	gas temperature (°C)
T_s	steel temperature (°C)
$T(x, t)$	temperature along the member length at coordinate x at time t, (°C)
w	applied gravity load (kN)
W	steel section weight per unit length (kg/m)
w_{DL}	dead load (kN)
$w_{LL,apt}$	arbitrary point-in-time live load (kN)
x	coordinate (m)
X	vector of random variables
$\alpha(T)$	thermal diffusivity as a function of temperature (m^2/s)
Δt	time increment (sec)
ΔT_s	temperature rise in steel (°C)
Δx	size of elements (m)
ζ	random variable with truncated lognormal distribution
κ	thermal conductivity (W/m C)
λ	eigenvalue parameter
ρ	density (kg/m^3)
ρ_p	density of SFRM (kg/m^3)

In the area of probabilistic fire following earthquake analysis, a framework was developed to evaluate the reliability of a 9-story moment-resisting frame (MRF) subjected to fire only and fire following an earthquake [8]. Four various limit states were defined for beams including plastic hinge formation, pseudo velocity, tension force, and deflection. The MRF was subjected to an earthquake record scaled to Maximum Considered Earthquake (MCE) followed by four post-earthquake fire scenarios. The study provided a general framework for the probabilistic assessment while considering uncertainties in fire load and temperature-dependent material properties. The effects of uncertainty in the active and passive fire protections as well as in the earthquake-induced damage (e.g., inter-story drift) and post-earthquake fire scenarios were, however, not incorporated in the analysis.

The above discussion highlighted few studies conducted on probabilistic structural fire engineering and fire following earthquake. This paper intends to extend previous studies on probabilistic structural fire to the area of fire following earthquake. Specifically, details of the development of a new probabilistic performance-based fire following earthquake (PBFFE) framework are provided. The framework is then used to develop fragilities of steel structural members and systems subjected to the cascading hazards of earthquake and fire. Uncertainties associated with the fire hazard (intensity and scenario), passive fire protection, gravity loads, and earthquake hazard are accounted for in the framework. The framework can provide means by which structural design engineers may assess alternative design scenarios for the multiple hazards and select the preferred design option based on a desired probability of failure.

2. Performance-based analysis framework for fire following an earthquake

Performance-based frameworks can be utilized by structural engineers to devise optimal and robust solutions for the design of structures under a given hazard considering all design constraints. The objective of performance-based engineering is to achieve a structural system that satisfies the needs of the stakeholders regarding performance levels at different hazard intensity. In the present study, a performance-based engineering framework is proposed for the sequential earthquake and fire hazards. The framework combines the PEER performance-based engineering approach for earthquake hazard [12], Fig. 1(a), with a newly developed framework for fire hazard, Fig. 1(b).

Although the utilization of performance-based engineering for fire hazard is straightforward in concept, the definition of variables involved in the framework, e.g., intensity measure, engineering demand parameter, and damage measure, remains quite challenging due to the complex nature and extreme variability in both fire loading and performance objective levels. Buildings need to meet minimum fire resistance requirements regarding insulation, integrity, and stability [4]. The current prescriptive fire design of steel structures is typically limited to specifying thickness of insulation materials for specific duration of fire. This prescriptive method does not take into account the probability of failure for the active or passive fire protections and the subsequent impact on integrity and stability of structural members and system as a whole. Since the present study deals with the multiple hazards of earthquake and fire, stability will be the primary focus. Insulation and integrity can be satisfied by non-bearing elements of building and stability can be provided by structural members and systems in such a way that the objectives of safe evacuation of occupants and protection of property are met.

An effort is placed in this paper on investigating four domains (hazard, structure, damage, and loss) of performance-based engineering for post-earthquake fire hazard, shown in Fig. 1(b) to identify an appropriate variable for each of the domains. The hazard analysis focuses on identifying intensity measure for fire. The intensity measure is defined using a hazard curve characterized by frequency of exceeding an intensity measure. Several parameters have been considered as intensity measure of fire in past studies, e.g., maximum gas temperature, duration of fire, peak temperature in a compartment, heat flux, among others. While these parameters are a viable option to serve as an intensity measure, fire load density, which is used in this study, could perhaps be the most suited intensity parameter for performance-based fire engineering. This is because it can be an adequate indicator of fire load measure considering all previously used parameters. Gernay et al.