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A simplified model for the post-fire earthquake flexural response of reinforced concrete walls with boundary elements

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ABSTRACT

A potential multi-hazard scenario for buildings is the sequential occurrence of fire and earthquakes, with such a scenario possible if a fire is triggered by an initial seismic event and a subsequent aftershock occurs. With fire negatively influencing the stiffness, strength, and deformation capacity of structural components, the building may be at risk for local or global collapse. The key role of reinforced concrete (RC) walls as lateral load resisting components make them of particular importance in considering the post-fire earthquake performance of buildings. Since the risk of fire-earthquake hazards is low, simplified models are needed to efficiently evaluate building performance. In this paper, a framework for simplified nonlinear modeling of RC walls is presented. The models are defined by modification factors that account for the change in wall response relative to that of a wall without fire damage. Modification factors, established from the results of a parameter study of walls using a verified simulation method, are a function of fire damage indices that account for the effect of fire on the material properties of steel and concrete. The dependence of wall response on most wall characteristics is eliminated by use of the damage indices, with the recommended modification factors dependent on the fire damage index and axial load alone.

1. Introduction

The evaluation and design of structures subjected to multi-hazards has been a topic of increased study in recent years [1]. Multi-hazard consideration for fire and earthquake is generally considered to be a sequential hazard, with an earthquake creating an increased likelihood of fire ignition [2]. At the same time, fire duration and severity is expected to increase due to damage to fire protection systems and of firefighter access restricted by damaged/blocked roads and bridges, as well as firefighter priorities shifting to other emergency response operations [3]. In such events, seismic damage may significantly impact the load-bearing fire resistance of structural components [4–6]. For structural components with no or minimal seismic damage, post-earthquake fire may significantly compromise the structural integrity and therefore have a significant impact on the performance in subsequent aftershocks [7–14]. Reinforced concrete (RC) structural walls are particularly important in the context of post-fire earthquake (PEF) events as they serve key functions for the resistance of both hazards (lateral load resistance for earthquake; physical barriers and load-bearing capacity for fire).

Frameworks for assessment and design of buildings have been developed for multihazards in general [1,15] and more specifically for post-earthquake fire [16] and mainshock-aftershock earthquake sequences, generally with a focus on how to account for probability of occurrence and how to link to building and/or structural component performance. However, utilization of such frameworks require the ability to accurately account for the structural response of building components. With large numbers of potential combinations of fire and seismic hazards, the ability to assess them via detailed analysis becomes challenging. Simplified analysis methods are needed that fit within the framework of how buildings are modeled for seismic hazards, are able to capture the effects of fire on the mechanical resistance to loads, and are able to simulate the seismic behavior accurately. Simplified modeling methods exist for both fire and earthquake loading and should be utilized in assessing post-fire seismic performance.

Simplified methods of accounting for fire effects on RC structural members can be achieved through methods and design aids provided by design codes and guidelines (e.g. EC2-04 [17] or ACI/TMS 216.1-14 [18]). These simplified methods allow users to identify the temperature at a particular distance from a heated surface via a suite of temperature vs fire duration curves. This in turn is used to identify modified material strengths used to calculate revised strengths. Further modifications from current fire analysis methods needed for post-fire earthquake are the changes to stiffness and deformation capacity.

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A number of simplified methods are available for seismic analysis of walls. Linear elastic models utilize stiffness modifiers to account for the flexibility of the structure and may be used to assess deformation capacity following the requirements of ASCE/SEI 7-16 [19] or to conduct preliminary assessment of existing buildings following the guidelines of ASCE/SEI 41-17 [20]. Backbone curves are provided by ASCE/SEI 41-17 to define the nonlinear response, including deformation capacity, to allow engineers to quickly define response characteristics for use in nonlinear models; backbone curves are provided for both shear- and flexure-controlled walls, with flexure-controlled walls having aspect ratios (height over length) greater than or equal to 2.0.

This paper presents a recommendation for modifying backbone curves of flexure-controlled RC walls to account for the effects of fire damage. The simplified models are recommended as an alternative option to calculate the stiffness, strength, and deformation capacity directly. Recommendations are developed using the results of detailed simulation for both the thermal and mechanical loading on the walls. The recommended simplified analysis method utilizes modification factors to account for the reduction in stiffness, strength, and drift capacity. Modification factors are defined based on fire-damage indices that account for the effect of fire on the mechanical response at the material level.

2. Fire impact on seismic resistance of RC walls

The simplified modeling approach for the post-fire seismic performance of flexure-controlled RC walls presented in this paper is based on findings of a parameter study of planar walls with confined boundary elements [21]. Details of the simulation procedure and in-depth analysis of the impact of fire damage on the stiffness, strength, and failure are documented by Ni and Birely [21,22]. Here, a brief overview of the models and findings are presented to support development of the simplified modeling approach.

A wall representative of planar wall characteristics in mid-rise buildings on the West Coast of the United States was used as the reference wall. Twenty additional walls investigated the impact of parameters that have the potential to affect the seismic performance of walls. Parameters included the axial load ratio ($p = P/A_W f'_{c,0}$), thickness (t_w), cross-section aspect ratio ($CSAR = l_w/t_w$), boundary element length (l_{be}), boundary element reinforcement ratio (ρ_{be}), web reinforcement ratio (ρ_{web}), and spacing of boundary element confining reinforcement (s). Fig. 1 shows the generalized cross-section of the wall and Table 1 provides the range of values for each wall characteristic considered; full details of the wall cross-sections are provided by Ni and Birely [21].

Walls were subjected to five thermal boundary conditions: no fire, 1-sided fire (long side exposed), 2-sided fire (both long sides exposed), 3-sided fire (one long side and both end exposed), and 4-sided fire. Fire-exposed sides were subject to radiation (emissivity coefficient 0.7) and convection (film coefficient 25 W/m^2°C). Unexposed side thermal boundary conditions were room temperature with film coefficient 9 W/m^2°C. The ASTM E119 fire curve [23] with durations of 0.25, 0.5, 1, 2, 3, and 4 h, followed by cooling at a rate of 5 °C/min, were applied to the first floor only. Heat transfer analysis was conducted using SAFIR [24]

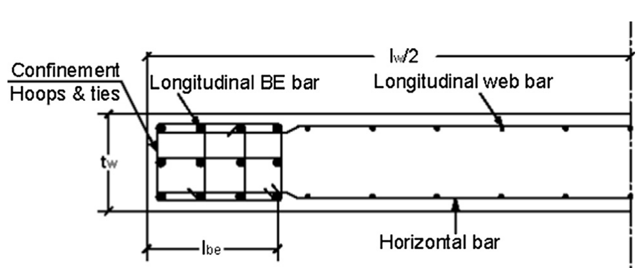

Fig. 1. Generalized planar wall characteristics.

Table 1
Summary of wall characteristics considered in model development.

Parameter	#	Min.	Max.
$p = P/A_w f'_{c,0}$	9	0.02	0.25
t_w (mm)	3	203	406
l_{be}/l_w (%)	3	10	20
$CSAR = l_w/t_w$	3	5	15
ρ_{be} (%)	5	1.11	4.39
ρ_{web} (%)	4	0.24	0.97
s (mm)	3	102	203

with thermal properties defined based on EC2-04. The lower limit of thermal conductivity for concrete is used. Post-processing used custom scripts to determine the maximum historic temperature (taken from the full heating-cooling cycle) in each steel and concrete fiber to define the post-fire residual material properties, which considers the effect of the cooling phase. These properties were used to define cross-sections of force-based beam-column elements with five-integration points in OpenSees [25]. The post-fire residual concrete properties are based on the recommendation by Chang et al. [26]. The post-fire residual concrete model is defined as a function of the maximum historic temperature concrete has experienced, including accounting for the cooling phase. The post-fire residual steel properties are based on the recommendation by Tao et al. [27]. Reinforcing steel exposed to temperature higher than 500 °C will not fully recover ambient strength after cooling to room temperature [27].

Seismic loads were applied with a reverse-cyclic displacement history, consisting of two cycles to drifts of increasing magnitude. Lateral load is applied as a single force at the top of the wall. Parameter study results [21] were reported as base shear forces; here base moment, equal to the base shear times the wall height, is used. Residual strains and stresses were not considered, but the impact on response has been shown to have minor impact, primarily on the wall stiffness [22]. Out-of-plane deformation has been shown to recover following fire [13], although may contribute to a premature out-of-plane local buckling failure of the wall. Axial loads were defined as a percentage of $A_w f'_{c,0}$, where A_w is the area of the wall cross-section, and $f'_{c,0}$ is the peak compressive strength of the concrete at room temperature. In order to ensure that the walls can be assumed to have a flexure-dominated response after the fire loading, the maximum shear (V_{max}) of the walls are compared to their nominal shear strength (V_n) (Eq. 18.10.4.1 in ACI 318-14 [28]). The ratios of V_{max} to V_n are significantly less than 1, which is consistent with the assumption that all the analyzed walls are flexure-controlled [21].

Fig. 2a shows the moment-drift envelopes for a wall with no fire, 0.5 h 4-sided fire, and 2 h 4-sided fire, illustrating the effect the fire has on the stiffness, strength, and drift capacity of the wall, where drift (Δ) is defined as the displacement at the top of the wall divided by the wall height. To quantify the response for a wider range of fire and wall characteristics, key response characteristics are extracted from the moment-drift (Fig. 2b) and moment-curvature (not shown) envelopes, where curvature is recorded at the lowest integration point. The stiffness (K) is defined as the secant stiffness at 75% of the maximum capacity (M). The drift capacity (Δ) and curvature capacity (ϕ) are defined as the point when the load decreases to 80% of the maximum capacity, or if not reached, the point immediately prior to a sudden decrease in the lateral load carrying capacity.

To characterize the effect of fire on the wall response, the stiffness, strength, and deformation quantities for fire damage, denoted by the subscript $_f$, are normalized by the same quantity for the wall without fire damage, denoted by a subscript $_o$. Fig. 3 shows a sample of the response of walls with different thickness subjected to four-sided fire of increasing durations. For all walls, the stiffness, strength, and curvature capacity decrease with increasing fire duration, however, the rate of decrease is greater in thinner walls. Fig. 4 shows the same information