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Impact of physical seismic damage on the fire resistance of reinforced concrete walls

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HIGHLIGHTS

- Investigated the effect of physical earthquake damage on fire resistance of RC walls.
- Walls with non-uniform reinforcement exhibit a complex deformation history.
- Seismic damage reduces both the thermal-insulation and load-bearing fire resistances.
- Insulation criterion controls the fire resistance of earthquake-damaged walls.
- The lateral restraint to walls mitigates the negative effect of earthquake damage.

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ABSTRACT

Numerical simulations are conducted to investigate the impact of physical seismic damage on the fire resistance of (steel) reinforced concrete (RC) structural walls. A wall with characteristics representative of typical construction in seismic regions is utilized as the basis of the simulations. A two-story wall is considered, with lateral restraint at all floors and at the top only to simulate loss of restraint from floor slabs. The behavior of an undamaged wall is assessed relative to the behavior of slices of walls typically explored in simulation studies. The non-uniform layout of reinforcement is shown to provide a complex deformed shape. Individual damage states, representative of damage observed following earthquakes and in laboratory tests, are introduced to the wall to assess impact on fire resistance. Cracking is shown to have a greater impact on the thermal-insulation fire resistance than on the load-bearing fire resistance. Cover loss or core concrete crushing in the boundary elements or web is shown to result in the possibility of increased out-of-plane deformations and decreased fire resistance. The location of cover loss has remarkable impact on the deformed shape of a wall and its load-bearing fire resistance. Lateral restraint at the floors provides significant support that minimizes the effects of damage on the load-bearing fire resistance. While the load-bearing fire resistance is reduced by damage in the wall studied, fire resistance times are not of concern; however additional studies would be warranted for thin walls and walls with large axial load ratios.

1. Introduction

Historically, the greatest losses due to fire following earthquakes have been due to the spread of fires from one structure to the next. Consequently, significant research, summarized by Lee et al. [1], has focused on understanding, modeling, and preventing the spread of fires. In modeling fire spread, emphasis is placed on sources of ignition and how fire moves from one structure to another. In such models, reinforced concrete (RC) buildings are generally assumed to be noncombustible and act as barriers to the spread of fire.

While post-earthquake fire in concrete buildings will not result in widespread damage to infrastructure and financial losses to the extent of fire spread seen in wood buildings in some previous earthquakes [2], the potential for loss at the individual structure level still exists. A number of recent experimental tests and numerical simulations [3–9], have demonstrated that seismic damage in RC structures can significantly reduce the fire resistance. These losses are of particular importance given that fires are more likely to start and to burn for extended periods of time following an earthquake. If the seismic damage prior to the fire allows for a more rapid spread of the fire within the building, such losses to

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building contents may be even larger. If the structural integrity of the structure is compromised due to the combination of seismic and fire damage, irreparable damage/deformations may occur that render the building unrepairable.

A detailed review of PEF provided by Mousavi et al. [10] includes a detailed history, mitigation strategies, and a two-step method for evaluation of building performance: 1) seismic analysis and post-processing to determine effects on characteristics that may impact fire resistance, and 2) thermal and/or thermal-mechanical analysis to assess fire resistance. Mousavi et al. identified PEF research needs, including experimental and analytical studies to inform development of guidelines for assessing PEF performance of structures.

The PEF performance of RC structures has been studied experimentally, although tests are typically terminated prior to failure. Shah et al. [7] tested four RC frames with and without ductile detailing. Each frame was subjected to reverse-cyclic loads followed by a compartment fire. Wider cracks and concrete spalling occurred in the frame with non-ductile detailing, leading to higher internal temperatures. Neither frame collapsed during the fire test. Meacham and Chen et al. [11,12] conducted a series of full-scale experiments on a 5-story RC building to investigate seismic performance of non-structural building systems and PEF performance of the building. The specimen was subjected to 13 ground motions on a shake table, followed by six fire tests on an upper story, with the tests primarily focused on the behavior of the non-structural components.

Due to the challenges and expense of conducting experimental studies of RC structures under sequential earthquake-fire loads, numerical analysis is an efficient method for investigating PEF performance. Wen et al. [3] used finite element models to analyze the fire performance of RC columns with concrete cover damaged. Results indicated that fire resistance decreases as the length of the damaged concrete region increased. Behnam et al. [4,8] conducted sequential pushover-fire analysis of single-story and multi-story RC frames. The negative impacts of concrete cover loss, residual deformation, section damage, and material degradation were taken into account. It was found that the fire resistance would decrease when significant seismic damage was present. Behnam and Ronagh [9] analyzed three-story frames with a natural fire curve. Mostafaei and Kabeyasawa [6] studied a six-story RC structure with seismic damage to columns; walls were included in the model, but damage to walls was not included. The effects of material degradation and heat penetration were found to significantly decrease the fire resistance of the structure, with cracking identified as the main contributor to reduced fire resistance.

This study is focused on investigating the post-earthquake fire resistance of RC structural walls to assess if there is a need to consider such a risk, and if so, what seismic damage(s) are most critical. RC walls are critical lateral load resisting elements that are found in both steel and concrete buildings and may also serve as load bearing walls and as fire barriers. Consequently, understanding wall behavior may be critical to assessing the PEF performance of many buildings. The objective of the study is to identify the impact of physical characteristics of damage and boundary conditions on seismic resistance. The methodology follows the outline provided by Mousavi et al. [10], with the first stage of modeling seismic response replaced by prescribed damage. Uncoupled thermal-mechanical analysis is conducted in ABAQUS/Standard using a standard fire curve. Prescribed damage, defined based on the worst-case possible damage observed following earthquakes or in seismic tests, allows for identifying the most-critical damage modes and the possible extent of seismic damage on the fire resistance. Standard fire curves, while not realistic of a long-duration post-earthquake fire, allow for a comparison to wall behavior reported in the literature.

2. Overview of wall characteristics and behavior

2.1. Seismic characteristics & behavior

In this paper, post-earthquake fire is considered for planar RC walls that serve as axial and lateral load resisting members. The wall studied is representative of typical characteristics of walls on the west coast of the United States, summarized by Birely [13]. Fig. 1 shows the geometry and reinforcement of the wall used in this study. Longitudinal reinforcement is concentrated in boundary elements at the edge of the wall, with hoops and cross-ties providing confinement to improve ductility during seismic loading.

Fig. 2 illustrates typical damage in RC walls. Flexural cracks form at the boundary regions. Shear cracking occurs in the web of the wall. Damage beyond cracking is concentrated in the "toe" of the wall, which is the lower region of the boundary element, and may include loss of cover, bar buckling or fracture, and crushing of the confined core [13–18]. In walls that have a mixed shear-flexure response or a shear dominated response, crushing of the web concrete may occur. The amount and extent of damage is dependent on many wall characteristics, including the reinforcement ratio, shear demand, and axial load. Much research, both experimental and simulation, has been conducted on the seismic performance of walls and is not summarized here; a comprehensive summary, including relationships between wall characteristics, seismic demands, and probability of damage, is provided by Birely [13].

2.2. Fire characteristics & behavior

When a wall is subjected to a fire, the heat transfer between the fire and wall is mainly by thermal radiation and heat convection

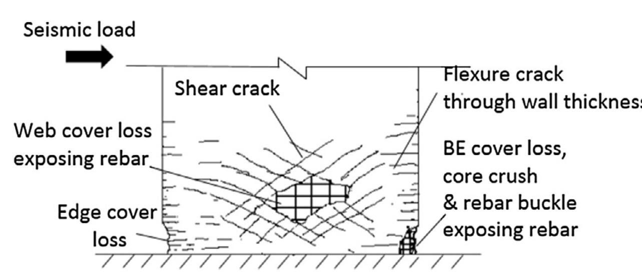

Fig. 2. Typical seismic damage to walls.

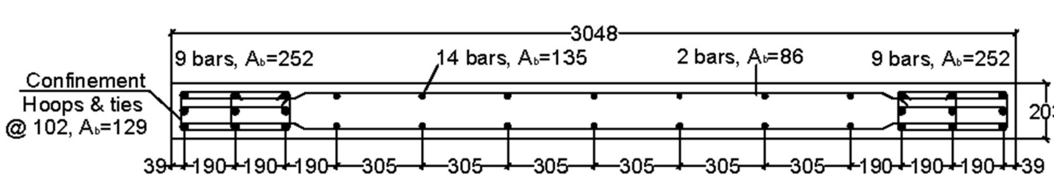

Fig. 1. Typical planar wall characteristics (unit: mm; A_b: cross-section area of one steel bar).