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Simulation procedure for the post-fire seismic analysis of reinforced concrete structural walls

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ABSTRACT

The impact of fire induced structural damage on the lateral load resistance of RC structures, particularly RC structural walls, is not well understood, but may be critical in the event of sequential fire-earthquake hazards. A simple verified simulation procedure for the post-fire seismic analysis of RC structural walls is necessary to advance the understanding of the post-fire seismic performance of RC structural walls. However, individual software programs which can do well in both thermal analysis and seismic analysis are not currently available. In this paper, a simulation procedure combining SAFIR and OpenSees is proposed for the post-fire seismic analysis of RC structural walls. The thermal analysis of a wall section is conducted in SAFIR while the seismic analysis of the fire-damaged wall is conducted in OpenSees based on the temperature data from SAFIR. The simulation method is verified by test data of RC walls under sequential fire-earthquake loads. The comparison of the numerical and experimental data demonstrated the capabilities of the simulation procedure to capture temperature distribution, stiffness and strength of flexure-controlled RC structural walls.

1. Introduction

While it is fortunate that the occurrence of failure of buildings under sequential fire-earthquake loads has not yet occurred, the potential for this sequential hazard to occur necessitates an understanding of structural performance for use in hazard mitigation. Such an event may result either from a significant fire occurring not long before an earthquake or as the result of a fire igniting as a result of an earthquake followed by a strong aftershock. While possible, the likelihood of these events is low and thus little research has been directed in the area. The ability to study these hazards is benefited by the availability of accurate yet efficient analysis tools. This paper presents a simulation method to do just this, focusing on the modeling of reinforced concrete (RC) structural walls under sequential fire-earthquake loads. RC walls are an important component to study due to their prominent role as both fire barriers and lateral load resisting systems.

Although not studied extensively, some valuable experimental research has been conducted on the seismic behavior of structural components previously exposed to fire loads. Xiao et al. [1] tested the post-fire performance of three high-performance concrete frames under reversed-cyclic loads. The fire transformed a strong-column-weak-beam frame into a strong-beam-weak-column one. Fifteen walls were tested under fire and then subject to reversed-cyclic loads by Liu [2] and it was concluded that fire damage decreases the lateral-load bearing capacity, stiffness and energy dissipation of structural walls. Compared to the decrease of lateral-load bearing capacity, the decrease of stiffness is much more severe. The decrease of stiffness and energy dissipation of fire-damaged walls has also been observed in the tests by Xiao [3]. In addition to the performance of fire-damaged RC structural walls under reversed-cyclic lateral loading, two fire-damaged RC structural walls have been tested under cyclic out-of-plane loading to determine the axial-flexural capacity of RC structural walls immediately after heating and after cooling down [4].

Since it is expensive to test RC structural members under sequential earthquake-fire loads, numerical investigation into this topic is indispensable. Franssen and Kodur [5] applied SAFIR to determine the residual load-bearing capacity of RC beams and columns and found that the axial restraint has a positive influence on the load-bearing capacity of fire-damaged simply supported RC beam and that the degradation of material, rather than the residual deformation, has more influence on the residual load-bearing capacity of RC columns under eccentric axial load. Mostafaei et al. [6] used VecTor3 [7] to analyze the performance of RC columns under monotonic lateral load and found that the lateral load-bearing capacity and ductility of RC column decreases noticeably due to fire exposure. Mo et al. [8] developed a computer program to investigate the influence of fire damage on the dynamic performance of

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fire-damage RC frames. Results show that the number of plastic hinge increases in the fire stories and is somewhat greater than the case with axial force. All of the numerical analysis mentioned above has indicated the negative effect of fire exposure on the mechanical performance of RC structures. However, more experimental validation of those simulation methods are required. Besides, none of those methods have demonstrated the ability of the numerical methods in analyzing the post-fire performance of RC structures under quasi-static cyclic loading.

For post-fire seismic performance of RC structural walls under quasi-static cyclic loads, a simulation procedure based on SAFIR [9] and OpenSees [10] is proposed in this paper. Different from the simulation methods mentioned above which use individual software programs, this simulation method combines the features of two different software programs, specifically thermal analysis in SAFIR and seismic analysis in OpenSees.

2. Existing software programs for the post-fire seismic analysis of RC structural members

The post-fire seismic analysis of RC structural members requires two steps: thermal analysis and seismic analysis. The thermal analysis captures the temperature distribution of RC structural members during the heating-cooling cycle. The temperature is used to establish the modified mechanical material properties of the concrete. These modified properties are then used in the seismic analysis. The seismic analysis captures the mechanical response of the fire-damaged RC structural members under the reversed-cyclic loads. It is difficult for individual software programs to do well in both thermal analysis and seismic analysis, but there are some software programs which excel at one or the other. Two programs are considered in this paper, SAFIR for thermal analysis and OpenSees for seismic analysis. The strengths of each are highlighted in Section 2.1 and 2.2. The use of SAFIR for thermal analysis could be replaced by the use of experimental data or other software programs capable of conducting the necessary thermal analysis.

2.1. SAFIR

SAFIR is a computer program developed at University of Liège. SAFIR can be used to study the behavior of one, two and three-dimensional structures subject to fire. Beam and columns can be modeled using line elements while slabs and walls can be simulated by planar elements. The material models for concrete and steel are based on those in EC2-04 [11]. SAFIR is able to conduct thermal analysis and structural analysis of a structure exposed to fire. The capacity of SAFIR in thermal-mechanical analysis has been demonstrated extensively [12–15], including modeling mechanical behavior due to thermal loadings. While SAFIR is a powerful tool for monotonic loading of RC components, the material models of SAFIR were not developed with the intent of use for cyclic analysis. Thus the mechanical analysis in SAFIR is not suitable for the studies of RC structures under reversed-cyclic loads. To demonstrate this, the reversed-cyclic analysis of specimen WSH4 [16] was performed in SAFIR. Fig. 1a shows the base shear vs drift hysteresis for the wall. The model is unable to capture unloading of the experimental test, showing a pinched response instead of the larger energy dissipation and residual drifts. Additionally, the strength is under-predicted and shows a strength degradation not seen in the experimental test. Most critically, the failure (crushing of concrete and buckling of longitudinal rebar) is not captured by the numerical analysis in SAFIR.

2.2. OpenSees

OpenSees (The Open System for Earthquake Engineering Simulation) [10] is an open-source software framework developed at the University of California-Berkeley to analyze the non-linear response of structural frames subjected to seismic excitations. OpenSees can successfully model the stiffness, strength, and hysteretic behavior of flexure-controlled RC walls with force-based beam column elements using the modeling recommendations of Pugh et al. [17]. In such a model, fiber-sections are used to define the section at each integration point. The uniaxial material models that define the fiber section are regularized through the use of material-dependent relationships to reduce the mesh dependency of the fiber-section models. This allows for accurate simulation of the flexural deterioration of softening wall sections [17].

In the material regularization, the crushing strain of unconfined concrete is modified to be

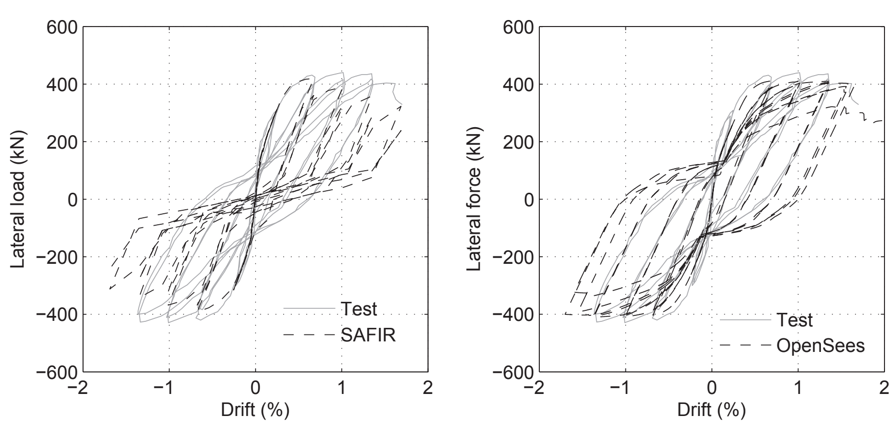
$$\varepsilon_{20u} = \frac{G_{fc}}{0.6 f_c^{'} L_{IP}} - \frac{0.8 f_c^{'}}{E_c} + \varepsilon_0 \tag{1}$$

where $f_c^{'}$ is the compressive strength of the concrete; E_c is the elastic modulus of unconfined concrete; ε_0 is the peak compressive strain of unconfined concrete; G_{fc} is the fracture energy of unconfined concrete in compression; and L_{IP} is the integration point length.

For confined concrete, the crushing strain of confined concrete is modified to be

$$\varepsilon_{20c} = \frac{G_{fcc}}{0.6 f_{cc}^{'} L_{IP}} - \frac{0.8 f_{cc}^{'}}{E_{cc}} + \varepsilon_{0c} \tag{2}$$

where $f_{cc}^{'}$ is the compressive strength of confined concrete; E_{cc} is the elastic modulus of confined concrete; ε_{0c} is the peak compressive strain of confined concrete; G_{fcc} is the fracture energy of the confined concrete in



(a) SAFIR (b) OpenSees

Fig. 1. Numerical lateral load-drift response of specimen WSH4.