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Effect of fire on in-plane and out-of-plane behavior of reinforced concrete frames with and without masonry infills

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HIGHLIGHTS

- A finite element model for fire response of RC frames and infill-frames is proposed.
- Validity of the model is established using appropriate experimental data.
- Masonry infill enhances post-fire in-plane stiffness of reinforced concrete frame.
- Masonry infill exacerbates out-of-plane stability of reinforced concrete frame.
- Fire has significant effect on room temperature failure modes of infill-frame.

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ABSTRACT

The present study develops a generic three-dimensional (3D) finite element (FE) model to characterize the in-plane and out-of-plane behavior of masonry infill reinforced concrete (RC) frames under fire exposure. The developed FE model accounts for critical factors governing thermo-mechanical behavior of these structural systems such as: temperature-dependent material properties, geometric and material non-linearities, cracking and crushing of concrete and masonry, and shear and tension debonding at interfaces. The developed model is validated using appropriate experimental data from the literature, and the validated FE model is subsequently utilized to investigate post-fire in-plane and out-of-plane behavior of masonry filled RC frames under standard and parametric fire exposures. The results from extensive parametric studies demonstrate that fire has a strong potential for degrading the in-plane stiffness and inducing significant out-of-plane instability in these structural systems, even for a small fire exposure duration of one hour. The results also reveal that the mechanism of degradation in in-plane stiffness of infill-frame is more intricate than that of RC frame, and presence of infill exacerbates the out-of-plane instability of RC frame under fire exposure. The developed model can be further utilized as a tool to develop performance-based design framework for rational fire design approach of these structural systems.

1. Introduction

The excellent thermal, moisture, and acoustic insulation properties along with global availability makes masonry an ideal construction material worldwide. Owing to these advantages, un-reinforced masonry infills are widely provided within reinforced concrete (RC) structural frames for providing partitioning in buildings. The masonry portion of these RC frames with un-reinforced masonry infills (infill-frames) is considered as a non-structural element by most of the building codes across the globe [1], thus, ignoring the structural interactions between masonry infill panel and RC frame. However, it has been well established through many experimental and numerical studies that it is important to incorporate the effect of masonry infills in order to determine realistic response of structural systems utilizing infill-frames [2–4]. The presence of these masonry infills have both positive and negative impacts on the structural behavior of RC frame structures. The positive impacts include enhanced initial stiffness, increased strength, and higher energy dissipation capabilities; whereas, negative impacts include susceptibility to buckling under eccentric loading, short column effect, and unwanted torsion. A comprehensive review of these positive and negative effects along with available

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methodologies for modeling infill-frames can be found in the literature [2].

These effects of masonry infill on structural behavior of RC frames have been extensively studied in the context of dynamic and static mechanical loading cases, however, studies pertaining to fire behavior are rather scarce in the literature. In case of fire, the positive effects of masonry infill can be undermined due to material expansion and degradation of strength and stiffness properties at elevated temperatures. Further, material degradation also causes a shift in the neutral axis of gravity loading, imparting additional eccentricity to the infill-frame, which can cause premature failure of the frame. While these adverse effects of fire on infill-frames have been acknowledged by researchers, the scientific community still lacks generalized and robust tools to assess this behavior.

Currently, prescriptive approaches are employed to assess the fire behavior of infill-frames. These approaches have significant limitations as they do not consider all factors governing fire behavior of infill-frames, such as material degradation at elevated temperatures, load intensity, level of restraint, and realistic fire exposure. This is primarily due to lack of validated numerical models capable of assessing the fire performance of infill-frames. Most of the previously developed numerical models for predicting thermo-mechanical behavior of infill-frames are two-dimensional (2D) idealizations [2]. Such models lack applicability over wide range of loading and fire exposures, and lack the ability to capture various failure modes of infill-frames.

Therefore, in order to bridge this knowledge gap and to better understand behavior of these structural systems under fire exposure, the present study proposes a three-dimensional (3D) finite element (FE) model developed in commercial FE program ANSYS [5]. The numerical model incorporates critical factors governing the thermo-mechanical behavior of RC and infill-frames, which are studied individually to compare the effects of presence of masonry infill on overall behavior. The numerical model is validated using relevant experimental studies available in the literature, and is subsequently utilized to perform parametric studies aimed at characterizing post fire in-plane and out-of-plane behavior. The results of numerical studies clearly demonstrate the strong potential of fire for instigating instability and degrading stiffness of infill frames.

2. Numerical model

The modeling approach for simulating the thermo-mechanical response of RC frames with and without infills is outlined in this section. While the present study implements this approach in ANSYS [5], any generic FE software can be utilized.

2.1. General considerations for infill-frame

Service loads on infill-frames often lead to localized failure mechanisms through cracks and slips, which have detrimental effects on the in-plane and out-of-plane structural behavior of the infill-frame. The effect of these failure modes on structural behavior is well explored, and a detailed review of such failure modes can be found in the literature [3]. Based upon various studies, it is acknowledged that the most crucial failure modes that a detailed FE model should be able to capture include: (a) sliding along bed and head joints, (b) cracking of the mortar, (c) cracking of the masonry blocks in direct tension, (d) diagonal cracking of the units where there is sufficient normal stress to develop friction in the joints, and (e) crushing of masonry [6].

However, incorporating all of these failure modes significantly enhances the level of complexities (convergence hurdles, computational effort, etc.) to the FE analysis of masonry structures, which necessitates introduction of certain simplifications to ease the analysis process. Most of these complexities are caused by a large number of interface elements. Thus, it is imperative to focus simplification strategies to minimizing the number of interface elements involved. In general, based on the desired level of accuracy and available computational resources, three main approaches are employed, as shown in Fig. 1 [3]. Out of these approaches, simplified micro modeling provides the most computationally efficient solution with the capability to capture the aforementioned failure modes [7,8]. Therefore, this approach has been adopted in the present study.

2.2. Thermal model

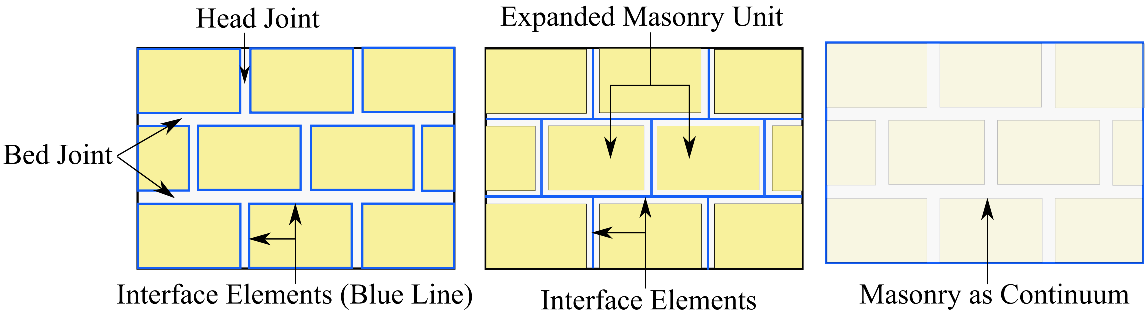
The heat transfer between hot fire gases and exposed surfaces of infill-frame occurs through thermal radiation and convection, whereas thermal conduction determines the development of temperatures within infill-frame [9]. This heat transfer can be modeled in a 3D physical domain Ω enclosed by boundary Γ in stationary coordinate system X, Y, Z as shown in Fig. 2. The domain is subjected to internal heat generation, Q, heat flux, h, and fixed temperature, $\bar{\boldsymbol{\theta}}$, boundary conditions. The governing energy balance equation for heat transfer within domain is given as [9]

$$\rho c \frac{\partial \theta}{\partial t} = \nabla \cdot (\boldsymbol{\lambda} \nabla \theta) + Q, \tag{1}$$

where, ρ is density, c is specific heat, θ is temperature, t is time, and $\boldsymbol{\lambda}$ is thermal conductivity tensor. The convection and radiation heat flux are applied in the form of surface loads as

$$h_c = \alpha_c(\theta_g - \theta_s), \tag{2}$$

$$h_r = \phi \epsilon_m \epsilon_f \sigma_{sb} \left[(\theta_g + 273)^4 - (\theta_s + 273)^4 \right], \tag{3}$$



(a) (b) (c)

Fig. 1. Different FE modeling strategies for masonry (a) Detailed micro modeling, (b) Simplified micro modeling, and (c) Macro modeling.