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Modeling the behavior of load bearing concrete walls under fire exposure

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HIGHLIGHTS

- A finite element based numerical model is proposed for tracing fire response of load bearing concrete walls.
- Validity of the proposed model is established.
- Results from model are utilized to characterize three distinct stages in fire response of walls.

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ABSTRACT

A generic three-dimensional (3D) finite element (FE) based numerical model is presented for predicting thermo-mechanical behavior of load bearing reinforced concrete (RC) walls exposed to fire. The proposed model is capable of accounting for critical parameters governing fire resistance of RC walls including wall slenderness ratio, support restrains, and temperature dependent properties of reinforcement and concrete. The model is validated by comparing predicted thermal and structural response parameters with the experimental data on three full scale load bearing RC walls tested under fire exposure. The comparisons show good correlation between model predictions and measured data, indicating that the proposed model can predict the thermo-mechanical behavior of RC walls from pre-loading to collapse stage under fire exposure. The validated model can be applied to undertake parametric studies aimed at quantifying critical factors governing fire performance of load bearing RC walls under fire.

1. Introduction

Reinforced concrete (RC) walls are widely used as vertical separations in buildings due to their cost effectiveness, architectural aesthetics, better space utilization, and low maintenance costs. These walls provide significantly higher axial and out-of-plane strength as compared to masonry infill walls, which results in small size requirements for the framing members; thus, leading to larger space and economical construction. Consequently, the use of load bearing RC walls in high rise building construction has gained popularity in the recent decades. In these buildings, RC walls are subjected to both in-plane (gravity loads from upper floors) and out-of-plane loads (arising from the eccentricity in gravity loading and/or wind loading); and play a key role in developing load transfer mechanisms in the building.

Typically, walls are to be designed for fire safety assuming one side fire exposure, and such a condition can develop steep thermal gradients within wall cross section. These thermal gradients cause uneven material degradation across wall cross section at elevated temperatures, which in turn imparts eccentricity to gravity loading. Thus, fire exposure has strong potential for inducing out-of-plane instability in RC walls. However, studies pertaining to fire behavior of walls, especially under eccentric loading, are rather scarce in the literature.

In case of fire, RC walls are expected to satisfy three criteria (failure limit states); which include ability to carry applied load under fire exposure (stability criterion), ability to keep temperature on unexposed face below ignition temperature (insulation criterion), and ability to provide fire compartmentation by preventing cracks and fissures (integrity criterion). Currently, these three criteria are assumed to be satisfied if prescribed member dimensions (for e.g. minimum thickness of the wall, concrete cover to main reinforcement etc.) are provided as per prescriptive code based specifications. Such prescriptive approaches are developed under

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standard fire conditions and do not take into consideration many critical factors governing the fire behavior of RC walls such as load level, wall slenderness, load eccentricity etc.

Moreover, there is lack of validated numerical models for predicting realistic behavior of RC walls under fire exposure. Most of the previously reported numerical studies on simulating behavior of RC walls under fire are either two-dimensional (2D) idealizations or do not account for all critical factors governing fire behavior of RC walls [1–5]. In order to overcome current drawbacks, a generic 3D finite element (FE) based numerical model is developed in ANSYS [6]. Comprehensive details of the model development along with its validation against fire test data are presented in this paper. Special consideration is given to incorporate thermal bowing and reverse bowing in evaluating structural performance under fire exposure, which play a key role in characterizing stability of concrete walls under fire exposure.

2. Behavior of RC walls under fire

There are limited numerical [1–5] and experimental [7–14] studies on behavior of load-bearing RC walls under fire. Some of the main findings in these studies are reported below.

2.1. Experimental studies

Crozier and Sanjayan [7] tested a total of eighteen load bearing slender RC walls (3600 mm × 1200 mm) by exposing them to standard fire exposure [15] on the tension face of walls. The varied parameters included wall thickness (75 mm, 100 mm, and 150 mm), clear cover to rebars (30 mm–110 mm), slenderness (24, 36, and 48 height to thickness ratio), concrete strength (44 MPa–70 MPa), and varying levels of eccentric in-plane loads. The in-plane load carrying capacity was evaluated through tests on eight wall specimens, supported on two short edges and subjected to eccentric in-plane and lateral loads –resulting from self-weight of the wall in horizontal position. Also, to investigate the effect of spalling and thermal bowing, eight additional walls were tested under the combined effect of gravity loading and standard fire exposure. Based on the results, the study concluded that (a) thermal bowing degrades the in-plane load carrying capacity of walls significantly; (b) strength of concrete had little influence on the fire behavior of RC walls; and (c) walls with vertical reinforcement at mid-thickness performed better than doubly reinforced walls (i.e. rebars at two outer surfaces).

It should be noted that testing of these walls in horizontal position led to development of significant flexural cracks on the tension side of walls, which led to degradation in fire resistance of walls. However, such flexural cracking is contrary to the service load conditions of walls, as walls are predominantly subjected to axial loads. This stimulated researchers to focus on providing realistic service loading conditions during fire tests, hence, most of the experimental studies after Crozier and Sanjayan [7] pursued testing of RC walls in vertical position along with appropriate support conditions [8–14].

Guerrieri and Fragomeni [8] tested four slender (1300 mm × 1300 mm × 50 mm) concrete walls, by exposing one face to standard fire exposure, to gauge fire induced spalling in walls. All walls were tested after a duration of six months from casting, with reported concrete strength to be approximately 40 MPa. Two of these walls were tested under the effect of self-weight alone, whereas, other two were subjected to an eccentric axial loading. In the tests, explosive spalling was observed in walls subjected to self-weight alone, and walls under eccentric loading did not experience any explosive spalling. This is explained on the account of relatively low flexural cracking in walls without eccentric loading. Flexural cracking allows dissipation of pore water pressure within wall under fire exposure, which reduces the risk of explosive spalling. Therefore, walls with relatively low flexural cracking are more prone to explosive spalling, which is reflected by results of the study.

Go et al. [9] studied the effect of aggregate density (normal weight, and light weight concrete), vertical reinforcement spacing (10 mm, 20 mm, and 30 mm), and width of wall (1000 mm and 1500 mm) on post-fire in-plane structural response of five RC walls (1500 mm × 75 mm). The concrete strength for all wall specimen varied between 20 and 22 MPa, and they were subjected to one sided standard fire exposure. The post-fire in-plane structural response of walls was compared with that of walls tested at room temperature, and it was concluded that lightweight concrete walls retained relatively higher in-plane strength, stiffness, and ductility as compared to normal weight concrete walls.

Lee et al. [10] studied the fire behavior of eight RC walls by exposing both faces of wall to standard fire exposure. The key variables of this study include: thickness of wall (100 mm–200 mm), load ratio (0–6%), amount of reinforcement (0.3% and 0.6% with equal vertical and horizontal reinforcement ratio), concrete strength (10 MPa–40 MPa), and curing duration of concrete (38 and 120 days). The results of the study show that thin wall specimens with shorter curing duration and high strength concrete are susceptible to premature failure under fire exposure. Kang et. al. [11] studied the effect of wall thickness (150 mm–250 mm) and moisture content (5–7%) on development of temperature profile within RC wall cross-section, and results of this illustrate the influence of moisture content on thermal response of RC walls.

Ngo et al. [12] studied the effect of eccentric loading (10 mm eccentricity), concrete strength (36 MPa–89 MPa), and polypropylene fibers on ten full-scale (2400 mm × 1000 mm × 150 mm) RC walls subjected to standard and hydrocarbon fire exposures. The results of the study show that all normal strength concrete (NSC) walls withstood fire exposure of 120 min with little or moderate spalling under standard and hydrocarbon fire exposure. However, walls fabricated with high strength concrete (HSC) experienced severe spalling in case of hydrocarbon fire exposure, which led to ultimate collapse of the wall at 31 min. The authors inferred that this spalling problem in HSC can be remedied to a certain extent by adding polypropylene fibers into HSC mix. This was shown through testing a wall by adding polypropylene fibers, which enhanced the fire resistance of modified wall to 65 min (from 31 min) under hydrocarbon fire exposure.

Mueller et al. [13] tested two load bearing RC walls (380 mm × 1020 mm × 3050 mm) with varying lateral restrains under standard fire exposure. Both walls had similar reinforcement detailing with an average test day concrete strength of 51 MPa and 47 MPa, respectively. The walls were subjected to an axial load of 2400 kN, representing constant dead load from superstructure, with fixed boundary conditions at the bottom. For one wall, the lateral displacement was constrained using an actuator at about 230 mm from the top of wall; whereas, another was subjected to a step wise incremental lateral load, pushing wall towards the furnace at the same location. The thermo-mechanical behavior was monitored using conventional strain gauges, digital image correlation, and infrared thermography. The results of this study revealed that constraining thermal bowing of RC walls can result in development of significant out-of-plane loads. Therefore, boundary conditions play a key role in characterizing thermo-mechanical behavior of RC walls.

Same experimental setup was further utilized by Mueller and Kurama [14] to evaluate the effect of concrete strength (47 MPa–123 MPa average test day strength), eccentric loading, wall thickness (203 mm–380 mm), reinforcement detailing, end restrains, and lateral loading on thermo-mechanical behavior of load bearing