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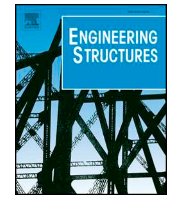

Predicting residual deformations in a reinforced concrete building structure after a fire event

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ABSTRACT

Reinforced concrete (RC) structures often remain stable under fire, but exhibit damage and residual deformations which require repairs. While repair operations and building downtime are expensive, current fire design approaches do not consider post-event resilience. The first step to enable predicting the resilience of RC structures under fire is to develop capabilities to model the damage of these structures after various fire exposures. This paper focuses on the prediction of the residual (post-fire) deformations of RC columns within a code-designed five-story RC frame building. Computational modeling approaches to capture the fire behavior of the columns are investigated. The models range from isolated columns with linear springs at the boundaries to full building model coupling beam and shell elements, with intermediate approaches. The analyses highlight the critical nonlinear role of the thermal expansion-contraction of the surrounding beams and slabs on the column deformations. Large transversal residual deformations develop particularly in perimeter columns, combined with residual shortening. This invalidates models based on isolated column or 2D frame. A parametric study of the residual deformations of RC columns is then conducted, with due consideration of the 3D restraints and interactions, to investigate the effects of different design parameters and fire scenarios on the residual deformations after a fire event. The results of the parametric study indicate that fire load density and opening factor significantly influence the residual deformations of RC columns, compared to the thermal conductivity of concrete and live loads. This research improves the understanding and provides recommendations for numerical modeling of the effect of fire on the residual capacity and deformations in RC structures.

1. Introduction

Reinforced concrete (RC) buildings generally exhibit a good structural performance under accidental fire events, as seen in, for instance, the 2005 Windsor Tower fire or the 2017 Grenfell Tower fire. In the two latter events, no global structural collapse of the concrete structure occurred, despite fires raging for hours. Yet, while fire does often not result in global collapse of RC structures, the potential loss due to downtime and repairs may be significant. In many instances, the fire accident is not as severe as in the two aforementioned cases, and a rehabilitation is possible [1,2]. The question of post-fire damage and downtime cost has gained increasing attention due to the requirements for resilience of structures under hazards. To develop optimum provisions to design fire resilient structures, engineers need the ability to accurately estimate the potential economic loss for different design alternatives due to fire damage. This in turn requires the ability to predict the behavior of RC structures under fire, including the residual deformations and residual load-bearing capacity of a structure after fire.

Structural members are often tested as independent elements under fire, disregarding global behavior. However, the proper inclusion of structural continuity of fire induced effects is crucial for an accurate evaluation of RC building's response. The heating of structural members leads to thermal expansion, which may cause the surrounding structure to impose high restraint forces. The significant impact of boundary conditions on the fire behavior of RC structures under fire has been observed in many historical accidents and previous research. In the Katrantzos Department Store fire (an eight-story RC building) in Greece in 1980, the restraints from differential thermal expansion in the structure led to the collapse of a major part of the 5th to 8th floors and the failures of various other floors and columns throughout the building [3].

Extensive research works have demonstrated the considerable effect of restraints on the behavior of RC structural members under fire, based on numerical or experimental studies of RC columns, beams, slabs and walls [4–11]. Therefore, proper modeling of these boundary restraint

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effects is essential when analyzing RC structures under fire.

However, previous numerical studies mostly adopted simple methods to simulate the restraint stiffness of structural components under fire, i.e. modeling isolated structural members under idealized boundary conditions. Those idealized conditions do not consider the variation of the surrounding restraints with fire, which stems from the change of restraint stiffness due to temperature degradation of the properties, as well as from the thermal expansion-contraction of the surrounding restraints [4]. Although some of the existing research has recognized the great deformation of the surrounding restraints, they have simplified the deformation of the surrounding structural members to an extent which even ignored the influence of critical structural components, for example, the sideway of a column under fire without considering the effect of the thermal expansion of slab [12]. Therefore, more research is required to propose a sophisticated yet computationally reasonable method to model the boundary conditions of a column part of a structure under fire.

Besides, previous research focused mostly on the heating phase for studying the effect of the surrounding restraints on the fire resistance of RC structural members, rather than investigating the post-fire residual deformations after heating-cooling. The structural behavior of concrete members is affected by both heating and cooling; severe damage may develop between the end of the heating phase and the full burnout, potentially leading to delayed failure [13]. To improve the resilience of RC structure under fire and minimize the economic loss from the fire damage of RC structures, the residual deformations of RC structural members after burnout should be accurately predicted.

Moreover, the concrete models used in existing research generally incorporate the effect of transient creep strain in an implicit manner. This does not allow capturing the effect on concrete behavior of the stress-temperature path nor the non-reversibility of the transient creep strain when the stress and/or the temperature is decreasing. While this limitation may be acceptable under heating, it is not appropriate under cooling and may lead to severe underestimating of residual deformations of a structural component after fire exposure [14–16].

To advance research on these issues, this paper focuses on the modeling of the residual deformations of RC structures after fire. The objective is to address some identified shortcomings with respect to the modeling of the effects of thermal expansion in structural assemblies as well as the effects of heating-cooling sequences and residual behavior, while accounting for sophisticated material models considering explicitly the transient creep strains. The fire behavior of a code-designed five-story RC frame is investigated. Numerical analysis by the finite element method (FEM) is adopted using SAFIR [17]. The main focus is on the behavior of the RC columns, while capturing the effects of interactions with the rest of the structure throughout the fire event. The behavior of RC columns as part of the full building model is compared to that of isolated columns under idealized boundary conditions. To reduce the computational cost, two intermediate modeling methods are introduced, where the structure surrounding the fire compartment is simplified. Those two methods aim to model the sophisticated boundaries of a column, notably the thermal expansion-contraction and the nonlinear response of the surrounding beams and slabs, while reducing the computational time with respect to the full building model. Results based on the intermediate models are compared to those from the full building model and the isolated column model. Then, parametric studies of the residual deformation of RC columns are conducted. These studies adopt the validated intermediate model. The parametric studies focus on four critical parameters, including fire load density, opening factors, thermal conductivity of concrete and live loads.

2. Prototype (code-designed) RC building

2.1. Description of the building

A five-story RC building was adopted as a prototype. The frame building consists of moment resisting frames in both orthogonal directions with 5 bays in each direction, having a 7.0 m span length, resulting in a 35 m by 35 m square floor plan (Fig. 1). A story height of 4.0 m was used for each floor including the ground level. The building was designed based on the 2010 NBCC seismic requirements with accompanying CAS Standard A23.3-04 “Design of Concrete Structures” used for proportioning and detailing of members [18–20]. The building is located in Vancouver and designed for residential or office occupancy with an importance factor of $I_E = 1.0$ (I_E is a function of risk category which is used to increase the margin of safety of a structure against collapse under earthquake [19]), on firm soil (Soil Class C). The design dead load included a superimposed dead load of 1.33 kPa consisting of floor finish, partition walls and mechanical/electrical fixtures, in addition to member self-weight. The live load was 2.4 kPa. It is designed to be a fully ductile frame, with $R_d = 4.0$ and $R_o = 1.7$ (R_d is the ductility-related modification factor reflecting the capability of a structure to dissipate energy through reversed cyclic inelastic behavior while R_o is an overstrength-related force modification factor accounting for the dependable portion of reserve strength in a structure designed according to the codes [19]). The characteristic compressive strength of concrete is 30 MPa and the characteristic yield strength of rebar is 400 MPa. Table 1 provides the design details for each member. The slab, designed according to CAS Standard A23.3-04 [20], is 200 mm in thickness, with two layers of reinforcement. The reinforcement ratio of the slab is adjusted in different regions based on ambient temperature design and according to construction practice.

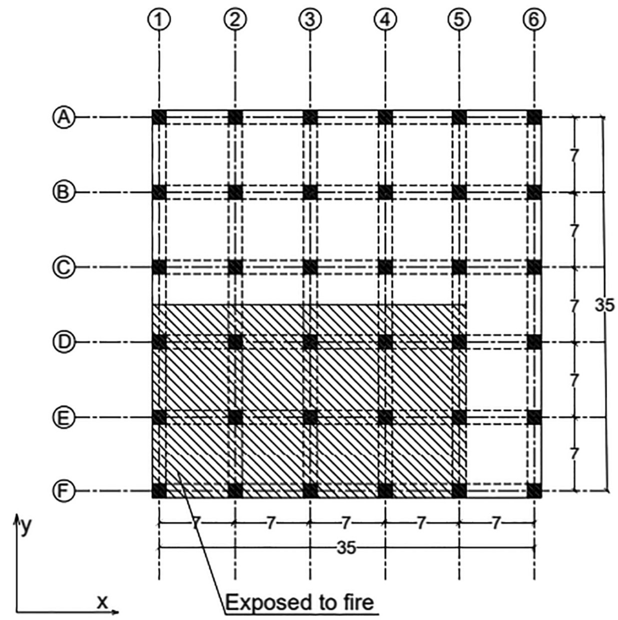

Fig. 1. Floor plan and region exposed to fire.

The building was designed for seismic loading [18], but no information was provided for the fire resistance of this building.

Table 1
Dimension of structural members.

		Size (mm × mm)	Steel reinforcement
Column	Corner Column 1–5	300 × 300	8–20 M
	Ext Column 1–2	300 × 300	4–30 M
	Ext Column 3–5	300 × 300	4–25 M
	Int Column 1–2	450 × 450	12–25 M
	Int Column 3–5	450 × 450	4–25 M + 4–20 M
Beam	Ext Beam	300 × 500	Top: 3–20 M Bottom: 2–20 M
	Int Beam	300 × 500	Top: 3–25 M Bottom: 2–25 M