COLLAPSE SIMULATION OF A TYPICAL SUPER-TALL RC FRAME-CORE TUBE BUILDING EXPOSED TO EXTREME FIRE

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ABSTRACT

The previous fire accidents proofed that reinforced concrete (RC) structures may experience progressive collapse subjected to extreme fires. In consequence, the study on the extreme fire-induced progressive collapse of RC structures is important for the safety of buildings. However, limited study has been performed on the extreme fire-induced progressive collapse of super-tall buildings. In this work, a finite element (FE) model and the corresponding elemental deactivation technology is proposed to simulate the extreme fire-induced progressive collapse of a typical super-tall RC frame-core tube building. The simulation discovered that the collapse of the building is initiated by the flexural failure of perimeter columns because of the thermal expansion of the floor system. The mechanism that discovered can provide a reference for related research of the fire safety of RC buildings.

KEYWORDS

Extreme fire, super-tall building, frame-core tube structure, progressive collapse, collapse mechanism

INTRODUCTION

Fire is a major threat to building safety. During an actual fire, the progressive collapse of the entire structure may occur following the local failure of structural components if the fire is extreme. However, limited research is available regarding the fire-induced collapse mechanisms of super-tall RC buildings in the literature. Consequently, the collapse resistances of super-tall RC buildings exposed to extreme fire are still unclear. Considering the dense population and high value inside super-tall buildings, the fire-induced progressive collapse of super-tall buildings can result in unacceptable financial losses and losses of life (Menzies 2001). Therefore, the study on the progressive collapse of typical super-tall RC buildings under extreme fire has a high significance. Fire-induced progressive collapse incorporates the behavior of the entire structure. Therefore, fire-induced progressive collapse should be analyzed from the perspective of the overall structure. Numerical simulation is one of the best methods to study the behavior of the overall structure.

Analyzing the fire-induced collapse of RC structures is much more complicated because of the complicated constitutive model of concrete and the non-uniform, time-changing temperature field distribution in each component section (Li *et al*. 2015). In addition to the challenges of simulating complicated temperature fields and constitutive models, the interactions of the structural components of super-tall buildings are much more complicated than those of multi-story buildings. Therefore, no research currently exists regarding the simulation of the progressive collapse of super-tall buildings.

Following the previous work of Li *et al*. (2015), a multi-layer shell element model is proposed in this study to simulate floor slabs and shear walls during fire. The FE model of a typical super-tall RC frame-core tube building is established using the proposed fiber beam element model and the multi-layer shell element model. The fire-induced progressive collapse of a typical RC super-tall building is simulated. The simulation results show that the thermal expansion and fire-induced failure of the floor system critically influence the failure of peripheral columns when multiple stories of a super-tall RC building are exposed to fire. Specifically, the progressive collapse of the building is triggered by the flexural failure of the peripheral columns due to the thermal expansion of floor slabs and beams. This work reveals the mechanisms of fire-induced progressive collapse in typical tall RC buildings and provides a method for studying the fire safety of tall RC buildings.

NUMERICAL ANALYSIS METHOD

Analysis process

The framework used to simulate the fire-induced progressive collapse of super-tall RC buildings is shown in Figure 1. An FE model of the overall structural system is established first. The numerical analysis is divided into the following three steps. (1) In the first step, gravity loads are applied to the structure at room temperature to generate the initial internal force in the structure. (2) In the second step, a selected fire scenario is applied to the structure to generate the temperature distribution field. (3) Finally, in the last step, the simulated temperature fields of the components are assigned to the structure as boundary conditions to perform the fire-induced progressive collapse analysis.

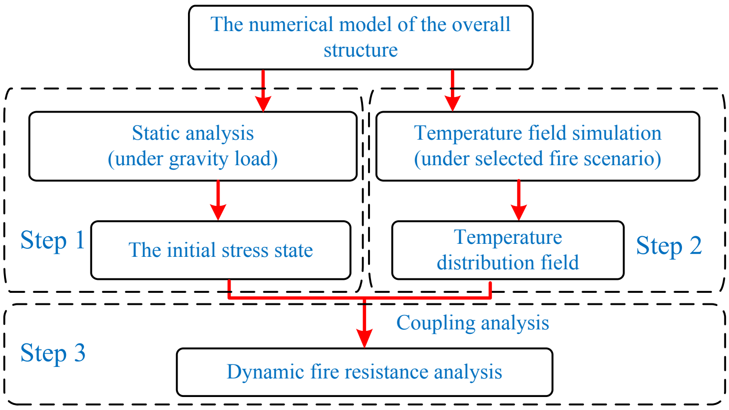


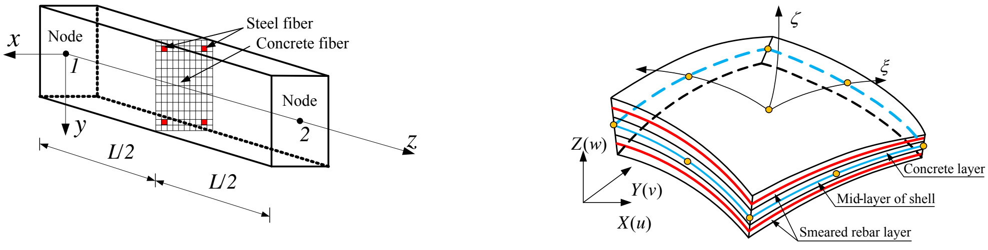
Figure 1 Framework for simulating the fire-induced progressive collapse of super-tall RC buildings

Numerical model

An accurate and efficient numerical model considering high temperature effects is critical for analyzing the fire-induced collapse of overall structures. The models for heated structural components and unheated structural components are introduced respectively as follows:

The unheated columns and beams are simulated using conventional fiber beam elements (Lu *et al*. 2013). The unheated shear walls, coupling beams and floor slabs are simulated using conventional multi-layer shell elements (Miao *et al*. 2011), as shown in Figure 2. Previous studies (Lu *et al*. 2013; Miao *et al*. 2011) have indicated that these models have satisfactory accuracy and efficiency for predicting the dynamic collapse of RC structures.

The temperature fields of RC components subjected to fire vary significantly inside the cross section and along the longitude axis. Therefore, based on conventional fiber beam elements and multi-layer shell elements, corresponding fiber beam elements and multi-layer shell elements are proposed for heated RC components. Different temperatures are assigned to different fibers or layers to account for the non-uniform temperature distribution within the cross-sections of the beams, columns, walls and slabs. The constitutive laws of the materials (Shi *et al*. 2002; Guo *et al*. 2003) that account for high-temperature effects are used to simulate the material behaviors subjected to evaluated temperature. A detailed introduction of the constitutive laws and element failure criteria is introduced by Li *et al*. (2015). The non-uniform temperature field along the longitudinal axis of the components can be considered by subdividing the component into many individual elements. The fiber beam elements and multi-layer shell elements are embedded into the general purpose FE code of MSC.Marc as user defined subroutines.



(a) Fiber beam elements (b) Multi-layer shell elements

Figure 2 Fiber beam elements and multi-layer shell elements

By comparing with the fire experiment results of different types of typical components, the proposed model can accurately predict the behavior of RC components under high temperatures. Furthermore, the computational efficient is high enough to satisfy the demands of overall structural collapse analysis. The validations of the numerical model are introduced in previous studies (Li *et al*. 2015; Li *et al*. 2011).

INTRODUCTION TO THE CASE STUDY

General building information

The studied case is a typical super-tall RC frame-core tube building which was designed by Lu *et al*. (2015) in accordance with JGJ3-2010 (2010). The building has 42 stories and a 6.1-m high penthouse on the top, with a total height of 141.8 m. Note that this building is also very similar to the typical super-tall RC frame-core tube building proposed by the Tall Buildings Initiative (TBI) project of the Pacific Earthquake Engineering Research Center (PEER) (Moehle *et al*. 2011). The three-dimensional model and planar layout of the structure are shown in Figure 3. The FE model of the building is established using the method proposed in Section 2.2, which contains 25,476 fiber beam elements and 17,352 multi-layer shell elements.

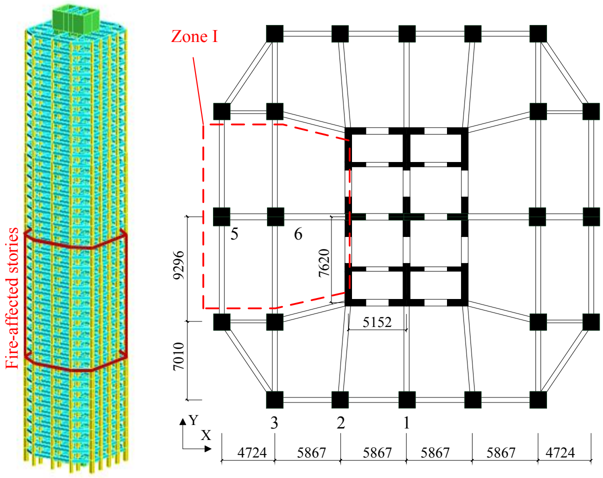


Figure 3 Structural arrangement and position of the fire-affected area (Unit: mm)

Fire scenario

Because no related reports are available regarding the fire-induced collapse of tall RC buildings, the most widely used International Standard ISO 834 (ISO 1999) standard temperature curve is used in this work to apply the thermal boundary condition, which refers to the fire resistance research (Frangi *et al*. 2004; Han *et al*. 2003) at the component level.

Because all of the tall buildings passed the conventional fire resistance requirement during the design procedure, only extreme fire loads can result in progressive collapse, which are much more serious than conventional fire loads. However, there is no related specification on such extreme fire in existing fire design codes (GB50016-2006 2006; National Fire Protection Association 2008) or progressive design codes (GSA 2008). Consequently, the fire scenarios in the collapse accidents of WTC and Windsor Tower will be used as important references. By considering the actual fire-induced collapse accidents of tall buildings, this study adopted a simplified extreme fire scenario in which a 10-hour ISO standard heating process is applied to multiple stories of a building. The fire spreading process is ignored due to the rapid vertical flame spreading speed in tall buildings (e.g., the speed of upward flame spreading in the Windsor tower was 6.5 min for each story). Of course, such a simplified extreme fire scenario cannot fully represent the complicated fire action of an extreme fire. However, note that this work is the first trial to implement the fire-induced progressive collapse simulation of tall RC buildings, and there are no previous widely accepted specifications on the fire action of extreme fire. Note also that the proposed simplified extreme fire scenario is convenient for other researchers to repeat the simulation in this work. Therefore, this simplified extreme fire scenario is adopted. Zone I is selected by considering the fire compartments in the building as typical fire-affected area (Figure 3).

The simulation of the temperature field

The thermal analysis module of MSC.Marc is used to predict the internal temperature field of the fire-affected components. The material thermal parameters, thermal radiation and convection parameters, which are required for temperature field analysis, are determined according to Eurocode 2 (British Standards Institution 2004). Subsequently, the calculated temperature field is transferred to the structural analysis module.

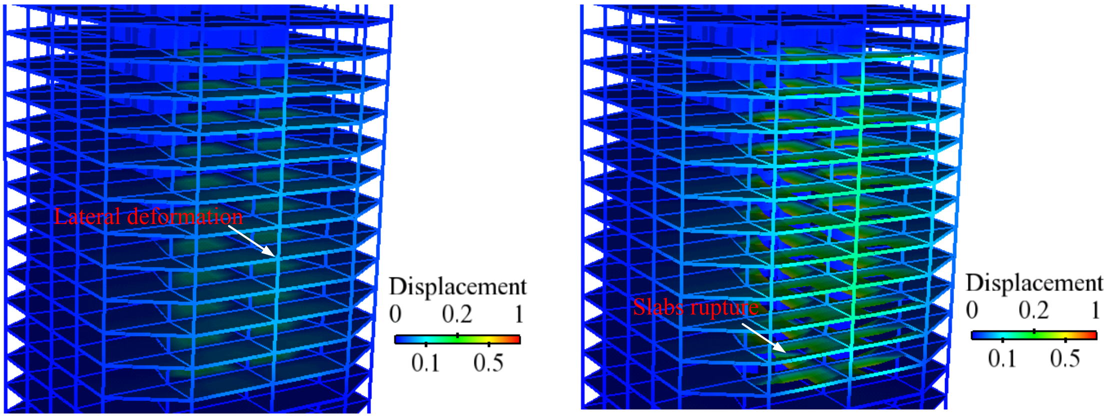
ANALYSIS OF FIRE-INDUCED PROGRESSIVE COLLAPSE

Fire resistance analysis is conducted for the case introduced above. The total computational time is approximately 60 hours on a computer with an Intel E5-2620 CPU and 64-GB of memory, which proves the computational efficiency mentioned above. After about 10 hours of fire exposure, progressive collapses occur in the case where most of the slabs, beams and columns in the fire-affected area collapsed.

Collapse process

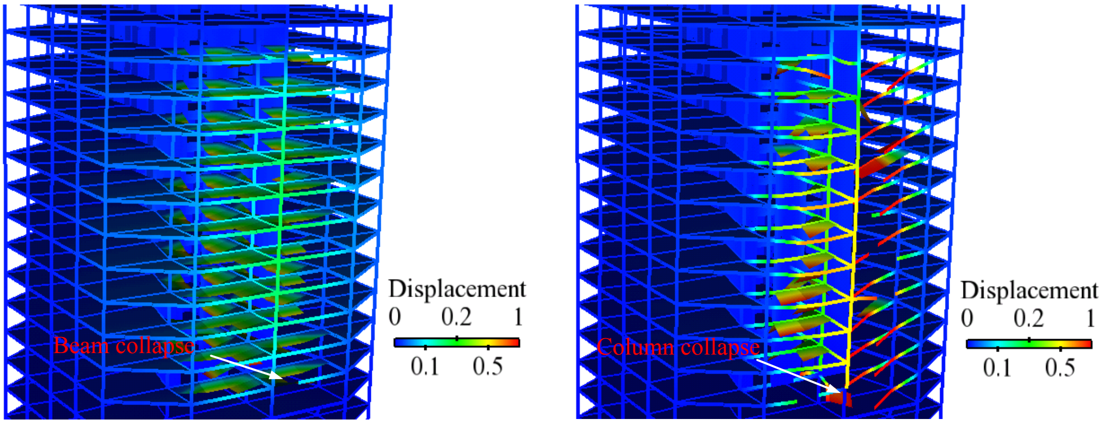
The case is discussed in detail in this section to illustrate the collapse process, failure mechanisms and interactions of different components in the building. For the convenience of the following discussion, the components in the building are named as “Column/Beam story number-component number”. The planar layout of the components is shown in Figures 3. For example, “Column 11-5” represents Column 5 (in Figure 3) on the 11th story.

The progressive collapse process is shown in Figure 6. As the temperature increases, the heated slabs are vertically deformed due to the combined effects of temperature and gravity loads. Simultaneously, because of thermal expansion, the slabs and beams push the peripheral columns outward. When t = 1.5 h, the peripheral columns laterally deform up to 5 cm (Figure 4a). When t = 3.3 h, the vertical deflection of the slabs reaches 50 cm. Meanwhile, the tensile strain of steel in the middle span of the slabs exceeds the ultimate strain and ruptures. However, such a local collapse of the slabs does not affect the stability of the entire structure (Figure 4b). When t = 6.5 h, most of the slabs in the fire-affected area collapse. In addition, the peripheral beams located on the lower stories of the fire-affect areas collapse. When t = 7.3 h, Column 11-5 collapses due to large lateral deformation (Figure 4d). The detailed failure mechanism of Column 11-5 will be discussed in a later portion of this work. Two seconds after the collapse of Column 11-5, Column 11-6 collapses, which triggers a progressive collapse (Figure 4e). Ten seconds after the collapse of Column 11-5, the fire-affected structure collapses completely (Figure 4f). Due to the large redundancy of the tall building, the collapse in the fire-affected areas does not cause further collapse in the residual structure.

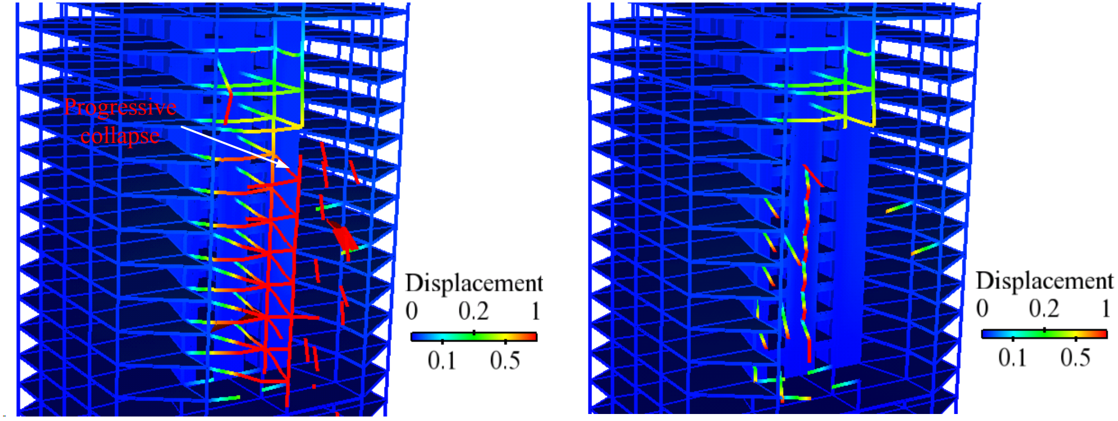


(a) Lateral deformation of peripheral columns (t = 1.3 h)

(b) Slabs began to fail (t = 3.3 h)



(c) Beams began to fail (t = 6.5 h) (d) Columns began to fail (t = 7.7 h)



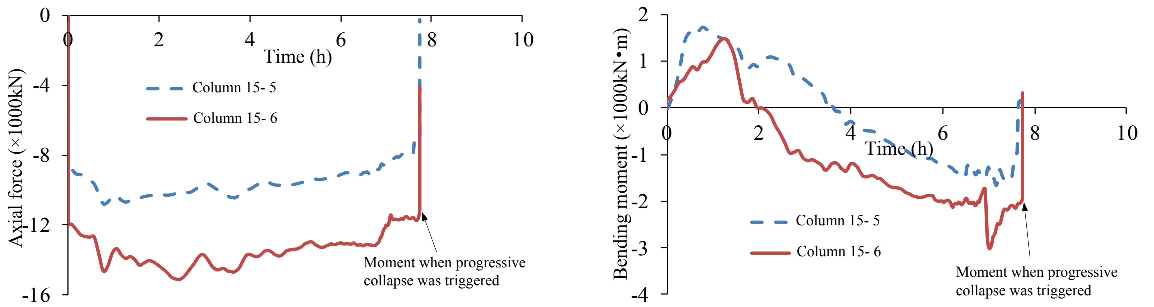
(e) Progressive collapse of structure (2 seconds after the columns failed) (f) Final failure mode (10 seconds after the columns failed)

Figure 4 Simulated progressive collapse process (unit: m)

Analysis of the collapse mechanism

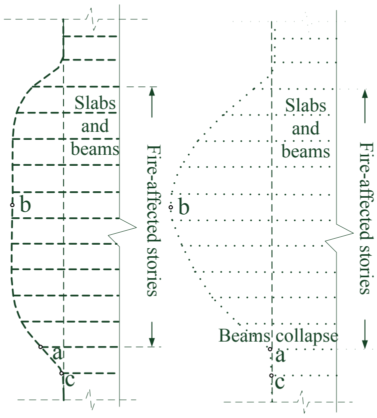
The numerical simulation introduced above shows that the failure of Column 11-5 triggers the progressive collapse of the entire structure. Figures 5a and 5b show the time histories of axial forces and bending moments in Columns 11-5 and 11-6. Before the progressive collapse (i.e., $t \leq 7.7$ h), the axial forces of the columns change significantly (up to 26.8%). The axial compressive forces increase firstly and then decrease when approaching to progressive collapse. In addition, the bending moments of the columns significantly change and the bending moments become reversed during the heating process due to the thermal expansion of the fire-affected floor slabs and beams.

The detailed collapse mechanisms are explained in Figure 6. During the initial phase of heating, the fire-affected stories pushed the column laterally outward due to thermal expansion. Figure 6a shows the lateral deformation of the column when $t = 3.3$ h. Subsequently, the fire-affected slabs and beams on the 11th through 13th stories fail one-by-one (Figures 4b). The push forces from the failed beams and slabs disappear, which results in the inward movement of Point a on the column due to the recovery of elastic deformation. Meanwhile, Point b on the column is continuously pushed outward by the thermal expansion of slabs and beams on the 14th to 20th stories. Such deformation results in a significant increase of curvature at Point a (Figure 7). Finally, Column 11-5 fails at Point a when $t = 7.7$ h due to extreme flexural deformation.



(a) Time history of the axial forces of the columns (b) Time history of the bending moment of the columns

Figure 5 Responses of the displacement and internal force of the columns



(a) t = 3.3h (b) before collapse

Figure 6 Deformation of the column (deformation magnification scale 1:40)

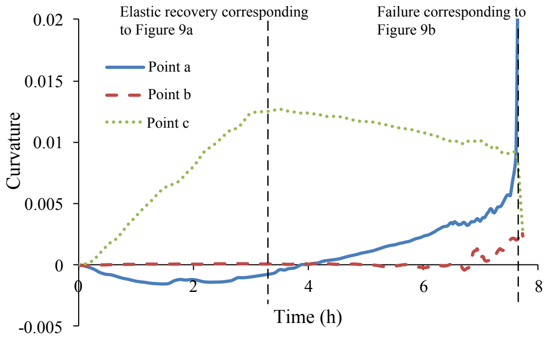


Figure 7 Time history of the curvatures of the column

CONCLUSION

In this work, the progressive collapse of a typical super-tall RC frame-core tube building exposed to extreme fires is simulated using the proposed numerical model. The primary conclusions are as follows:

(1) When subjected to extreme fire loads, progressive collapse may occur inside the fire-affected area. However, because of the large redundancy of a super-tall RC frame-core tube building, the structures outside of fire-affected areas can avoid progressive collapse via alternative load paths.

(2) The progressive collapse of a super-tall RC frame-core tube building is triggered by the flexural failure of the peripheral columns, which are pushed outward by the thermal expansion of the floor system.

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