BEHAVIOUR OF PRE-FIRE AND POST-FIRE PERFORMANCE OF ECCENTRICALLY LOADED SRC COLUMNS AND JOINT

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Abstract – *Fire has become one of the greatest threats to buildings. It could dramatically reduce the strength of reinforced concrete structures. This paper studies the pre-fire and post-fire performance of steel-reinforced concrete (SRC) columns subjected to an entire loading and fire phase, including ambient temperature loading, heating and cooling with external load, and post-fire loading. To improve the precision of the FEA model, the influence of fire-induced concrete explosive spalling (CES) was considered by using element change technique. Here we using SRC column with I-shaped steel and the test results are adopted to verify the FEA modeling. The objective of this work is to study the behaviour of I- shaped SRC columns exposed to fire under axial load and to evaluate column compressive capacity after fire. The main studying parameters are the strength of I-shaped SRC columns, failure mode and deformation after fire exposure considering parameters such as fire duration, steel ratio and eccentric loading. Besides the fire-resistance test data of SRC columns applied in a beam-column joint of a high rise building with external loads to further validate the accuracy of the FEA model in the post-fire phase, a set of fire tests on SRC columns, including a fire-resistance test and post-fire test subjected to the entire loading and fire phase to be conducted. With the test program, the influence of parameters such as the eccentric loading, the fire duration time and the steel ratio on the pre-fire and post-fire loading of beam-column joint are to be investigated.*

Key Words: Steel Reinforced Concrete(SRC), Beam-to-Column joint, Standard fire, Heating phase, Cooling phase, Post-fire phase, Spalling, Finite element analysis(FEA) model, Composite structures.

1. INTRODUCTION

Fire is a frequent disaster among all natural disasters possession. In recent years, a large number of high-rise and super high rise buildings were built or will be built. These buildings are generally equipped with the best fire protection system. In recent years, steel reinforced concrete (SRC) structures are widely used in high rise buildings because of its high load bearing capacity, good ductility, high stiffness and enhanced fire performance compared to most other structural forms. To promote the application of SRC structures, relevant design codes, such as ISO-834, ACI 318 (ACI 2005), EN 1994-1-1 (CEN 2004) and JGJ 138-2001 (JGJ 2002), have been proposed by different committees or countries. In terms of the fire performance of SRC columns, conducted by Han et al(2015)[2] was proposed a simplified formula to calculate the fire resistance of SRC columns. He investigated this formula by considering parameters load ratio, sectional perimeter, slenderness ratio, steel ratio and strength of concrete. Ming-Chin, Ho and Chen-Hung Lee(2014)[3] investigate the behaviour of large-scale steel reinforced concrete structures (SRC) in fire through a series. The material properties at elevated temperatures, behaviour of structural elements in fire, assessment of fire-structure safety and design code are involved in this project. Tan and Han(2013)[5], was developed an analysis procedure for steel reinforced concrete (SRC) columns after exposure to fire and subsequent strengthening to calculate the bearing capacity and flexural stiffness of SRC columns after exposure to fire. Moura Correia and Rodrigues (2011)[4],were studied the parameters load level, the axial and rotational restraint ratios and the slenderness of the column. The main conclusion of this work is that for low load levels the stiffness of the surrounding structure has a major influence on the behaviour of the column subjected to fire. Increasing the stiffness of the surrounding structure led to reductions in the critical times. The same behaviour was not observed for the high load levels. Young and Ellobody(2010)[6], investigated the structural performance of axially restrained concrete encased steel composite columns at elevated temperature. An efficient nonlinear 3-D finite element model was presented for the analysis of the pin-ended axially loaded columns temperatures. The columns investigated had different cross-sectional dimensions, different coarse aggregates and different load ratios during fire.

Set against this background, this paper establishes an FEA model by modifying the original FEA model in Han et al. (2015)[2] to analyze fire-resistance test data of SRC columns using Indian standards applied in a beam-column joint of a high rise building with external loads to further validate the accuracy of the FEA model in the post-fire phase. With the test program, an entire loading and fire phase and post-fire loading of beam-column joint including cooling are to be investigated.

1.1 Brief Summary of SRC structures

Steel Reinforced Concrete (SRC) structures are composed of shaped steel, reinforcing bars and concrete. In such composite sections, the ulterior concrete can act as a sacrificial layer for the interior part under fire. The concrete has a much lower heat conduction coefficient, so the rise of temperature in the shaped steel and reinforcing bars could be effectively retarded and reduced. Therefore, SRC structures have a higher fire resistance in comparison with other steel structures. Because of its advantageous structural performance, such as high stiffness and strength, excellent seismic-resistant and good fire performance, this type of composite structure system has been attractive to civil engineers and researchers.

1.2 Objectives

The project focussed on the behaviour of different I- shaped SRC columns exposed to fire under eccentric loading and to evaluate column compressive capacity after fire. An effect of fire exposure and post fire phase including cooling in a beam-column joint of a high rise building is investigated.

2. MODELING AND ANALYSIS

2.1 Element Selection

A total of four SRC column specimens with I-sections were selected. ISLB 150, ISLB 175, ISMB 150, ISMB 175. The shaped steels were fitted with a steel end plate with a thickness of 40 mm at top end in order to avoid local buckling. Solid65 element is used for concrete and Link 180 element for flexural and shear reinforcement for structural analysis. Eight 18mmφ steel bars were used as longitudinal reinforcement. 8mmφ steel bars were used as stirrups, and the space between stirrups was 200 mm. The length of the column specimen excluding the end plates was 3,810 mm.

The unit weight of steel is 7850 Kg/m^3, modulus of elasticity is 205100 N/mm^2 and the poison's ratio is 0.3. Tensile strength of I section is 307 N/mm^2. The density of concrete is taken as 2300kg/m3. The short-term modulus of elasticity of concrete is taken as 21080 N/mm^2. Tensile strength of I section is 307 N/mm^2 and the poison's ratio is 0.21.

2.2 Meshing and Boundary Conditions

Behavior of SRC column with bottom end fixed support condition and top end loaded at different eccentricities is evaluated for different time of exposure. The effect of fixed support condition is analyzed. To study the effect of eccentricity in load, the same column with a load of 2000 kN placed axially, at 0mm, 45mm, 90 mm eccentricity and at 120 mm eccentricity is studied.

2.3 Temperature Field Prediction

The thermal boundary conditions were defined according to the recommendations in Eurocode 4 (European Committee for Standardization 2005). A constant convective heat transfer coefficient of 25 (Wm−2K−1) was assumed for the fire exposed surfaces and the corresponding resultant emissivity was taken as 0.7 for concrete surface according to Eurocode 4 (European Committee for Standardization 2005). Tie constraint was adopted to simulate the interfaces between steel bars and concrete, shaped steel and concrete. For the concrete exposed to fire conditions, concrete spalling may occur at different fire stages, such as the early stage, intermediate, and later fire stages. For concrete spalling occurring at the intermediate and later fire stages, its mechanism is complex and its occurrence conditions are still uncertain.

2.4 FEA Modeling of SRC Column

Fig. 1(a) & (b) shows the arrangement of the specimen used to model FE model. The model consists of an ISMB 175 SRC column with different eccentricities.. The commercial FE program ANSYS software is used to establish the FEA modeling, which includes temperature field prediction and structural analysis. Descriptions on the thermal and mechanical properties for steel and concrete at high temperatures, the steel-concrete interface, element type, and other modelling techniques are subsequently introduced.

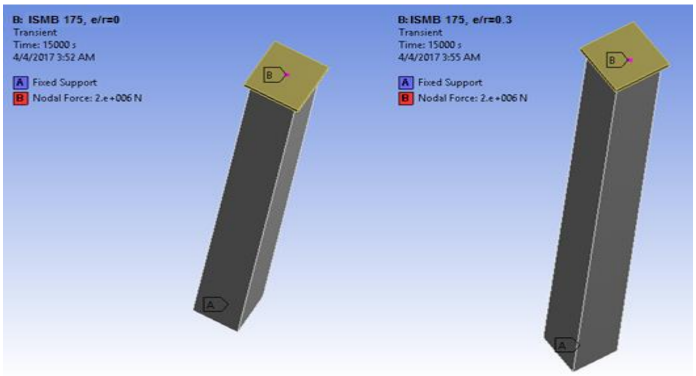

Fig -1(a): Modeling of SRC column

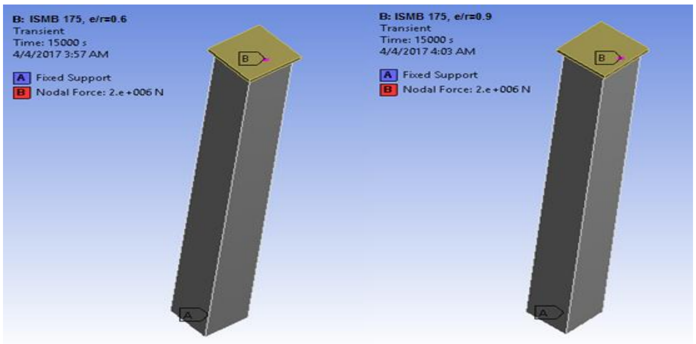

Fig -1(b): Modeling of SRC column

3. BEHAVIOUR OF COLUMN ON FIRE EXPOSURE AND AXIAL LOADING

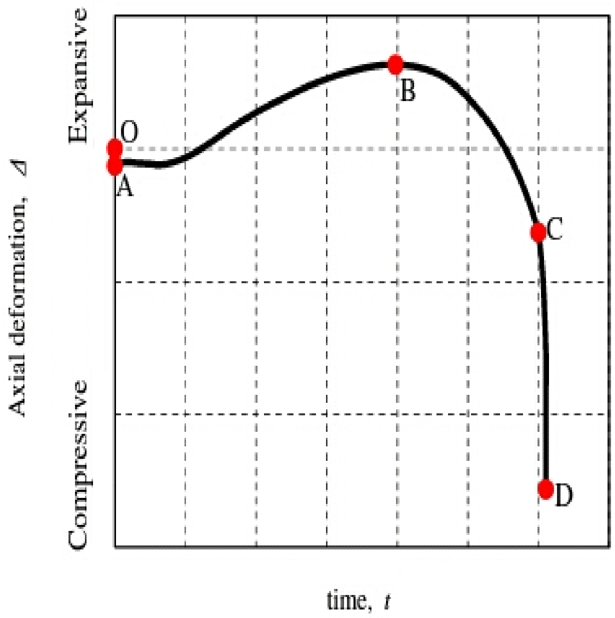

Fig -2: Typical SRC Column Axial Deformation versus Time Curve

1. Ambient loading stage (O–A). During this stage, the initial load is applied on the SRC column before exposure to fire, and the Δ-t relation looks linear approximately.

2. Expansive stage (A–B). During this stage, the load on SRC column remains constant, and the column is exposed to ISO-834 (1975) standard fire. As the material temperature rises, material thermal expansion and degradation occur at the same time. However, in this stage, the effect of axial thermal expansion suppresses the effect of material degradation, and the expansive deformation of the column is observed. When the effects of material expansion and degradation are balanced, the expansion displacement reaches to the peak value at Point B.

3. Softening stage (B–C). During this stage, the load is still kept constant while the temperature increases further. As the fire temperature increases, the contractive deformation induced by the material degradation becomes dominant. The axial deformation of the column changes from expansive to compressive.

4. Accelerated failure stage (C–D). In this stage, the second-order effect induced by the axial force is dominant, therefore the axial deformation of the column increases rapidly and the column fails when the maximum axial contraction or the rate of contraction reaches the failure criterion specified in ISO- 834-1 (1999).

4. FEA ANALYSIS OF COLUMN

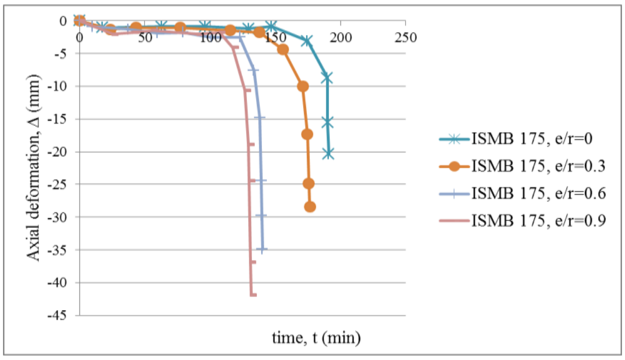

Fig -3: SRC Column (ISMB 175) Axial Deformation versus Time Curve

SRC Column ISMB 175 with one end fixed and other end loaded with 2000kN. The results indicate that as the column is subjected to eccentric load, its fire resistance decreases with increase in restraints. It may be due to the reason that an eccentric load induces an additional moment on the column producing excessive lateral deflection and causes stiffness reduction; which in turn reduces the capacity of column causing failure.

Specimen ISLB 150, ISLB 175, ISMB 150, ISMB 175 was tested. In the heating phase of composite column ISMB 175 is better than others. So that the performance in the cooling stage and postfire behaviour of beam-to-column joint could be studied using ISMB 175. The detailed test results are introduced subsequently.

5. FIRE EXPOSURE BEHAVIOUR OF BEAM-COLUMN JOINT

In this, an entire loading and fire phase, including ambient temperature loading, heating and cooling with constant loads, and postfire loading, was adopted to investigate the postfire performance of SRC joints. The research provided useful information to understand the postfire performance of SRC joints. In reality, the joint in a global structure is always restrained by the adjacent components, and because of the interactions between the joint and the adjacent structural.

5.1 Brief Description of the Specimen

SRC column to SRC beam joint specimens with RC slabs were designed under the design principle of strong column–weak beam. The steel beam segments were welded to the steel column first, followed by the installation of the reinforcing steel cages for the SRC column, SRC beams, and RC slab. Then, the concrete was poured to form the composite joint. The height of the SRC column (H), including the two end plates, was 3,800 mm, and the lengths of the SRC beam (L) and RC slab (Lslab) were 3,900 and 2,000 mm, respectively. Table 1 presents the other dimensions of the joints, where D_c and B_c is the depth and width of the cross section of the SRC column respectively; h_c and b_{fc} are the depth and width of the H-shaped steel in the column, respectively; t_{wc} and t_{fc} are the web and flange thicknesses of the H-shaped steel in the column, respectively; D_b and B_b are the depth and width of the SRC beam section, respectively; h_b and b_{fb} are the height and width of the H-shaped steel in the beam, respectively; t_{wb} and t_{fb} are the web and flange thicknesses of the H-shaped steel in the beam, respectively; b_{slab} and t_{slab} are the width and thickness of the RCC slab, respectively.

Table -1: Details of joint specimens

SRC column (mm) ISMB 175	D_c	300
	B_c	300
	h_c	175
	b_{fc}	90
	t_{fc}	8.6
	t_{wc}	5.5
SRC beam (mm) ISMB 175	D_c	300
	B_b	200
	h_b	175
	b_{fb}	90
	t_{fb}	8.6
	t_{wb}	5.5
RC slab (mm)	b_{slab}	1000
	t_{slab}	100

6. FEA MODELING OF SRC BEAM-COLUMN JOINT

A FEA model was developed to simulate the behaviour of the tested SRC beam-to-column joints. A heat transfer analysis model was established first to obtain the temperature distribution in the joint, and then the temperature data corresponding to each node were imported into the structural analysis model to simulate the fire or postfire performance of the joint specimen. The same mesh division used in the heat transfer analysis is adopted in the structural analysis. Solid elements are used for the concrete and end plates, shell elements for the H-shaped steels, and truss elements for the steel bars. The bottom end plate of the column is fixed, the top end plate of the column is restrained and the two ends of the SRC beams are free.

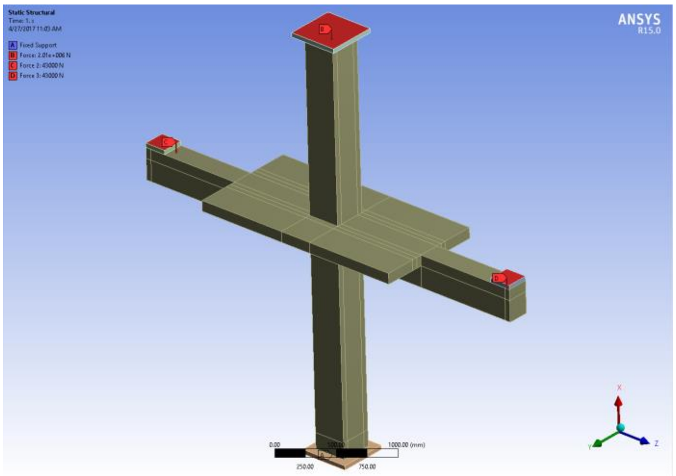

Fig -4: Modeling of SRC beam-to-column joint

6.1 Test Procedure

To investigate the performance of SRC beam-to-column joints during the entire loading and fire duration, the following test procedure was employed:

6.1.1 Ambient Temperature Phase

A joint specimen was installed in the furnace and connected with the loading system at an ambient temperature. The bottom end of the column was fixed, and the top end of the column was restrained against all directions except the vertical direction. The two ends of the beam were free from restraint. Axial load (N_F) was applied to the column, and two vertical loads (P_F) were applied to each end of the beam on each side of the joint. In this test, N_F and P_F were taken as 2,120 and 43 kN, respectively.

6.1.2 Heating Phase

The applied loads on the column (N_F) and beam (P_F) were kept constant, and the space under the RC slab was heated, as marked in Fig. 6.2. In this phase, the furnace temperature was controlled following the ISO-834 (ISO 1975) heating curve, and the fire was continued until the fire resistance or predetermined heating time (t_h)

6.1.3 Cooling Phase

For Specimen, after the predetermined heating times were reached, the furnace door was opened and the specimens were cooled down to room temperature. In the cooling phase, the loads applied on the column and beam was kept stable until the specimen cooled to an ambient temperature. The entire cooling phase took approximately 20 h.

6.1.4 Post fire Phase

After the specimen cooled to the ambient temperature, the loads on both the left and right beam segments were increased at the same time until the joint failed at an ultimate load on each beam segment. During the loading stage, the column load (N_F) was kept stable.

6.2. Failure Modes of Beam-Column Joint

All specimens showed similar failure modes, demonstrating strong column–weak beam behaviour. The failure of the joint specimens was primarily concentrated in the SRC beams. For the fire resistance test specimen, a major crack occurred on the top surface of the RC slab close to the SRC column, which induced a remarkable increase in right beam deflection.

Owing to the development of the tensile stresses, a number of concrete cracks occurred on the top surface of the RC slabs. For the fire resistance test Specimen, with the development of concrete cracks on the top surface of the RC slab, a major crack close to the SRC column induced the fracture of the RC slab, and the joint failed to support the beam loads at the end of the fire testing.

6.2.1 Deformation Development

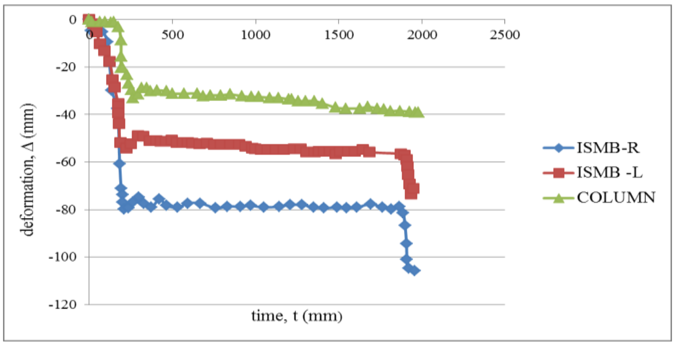

Fig -5: SRC Column (ISMB 175) Axial Deformation versus Time Curve

Fig.4 shows the measured column axial deformation (Δ) versus time (t) curves of the three joint specimens, respectively. For the postfire test the Δ-t curves can be generally divided into three phases. i.e., (1) heating phase, (2) cooling phase, and (3) postfire phase.

At the beginning of the heating phase, axial elongation was observed, because of the thermal expansion of materials. . In Phase I, axial elongations were observed. In Phase II, with the cooling of the furnace, increasing axial contraction occurred for the SRC columns, primarily because of the cooling contraction of the materials. In Phase III, with the increase of beam loads, the column axial contractions increased, but not significantly, because the beam loads were relatively low compared with the loading capacity of the SRC columns.

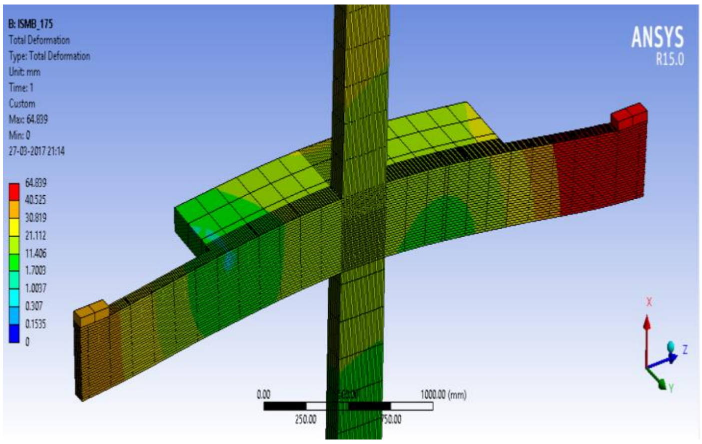

Fig -6: Heating deformation of SRC Beam-Column joint (ISMB 175)

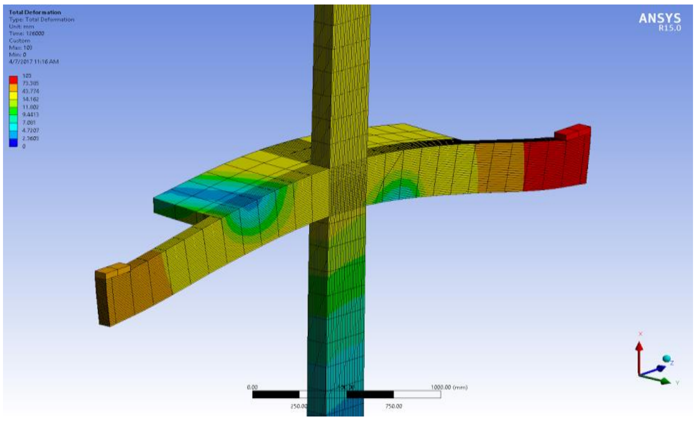

Fig -7: Cooling deformation of SRC Beam-Column joint (ISMB 175)

For beam specimen, in the heating phase (I) and at the beginning of the cooling phase (II), the beam vertical deformations increased significantly because of degradation of the material properties. After that, the change of beam vertical deformations was minor until the end of the cooling phase. In Phase III, the left and right beam loads were increased at the same time until the joint failed, with beam deformations exceeding the failure criteria. Specimen failed when a load of 45kN was applied on its right beam. The deformation increment occurring in the cooling phase is much larger than that occurring in the heating phase. . The increment in the cooling phase is approximately 1.6 times that of the heating phase. This observation highlights that the cooling phase should be considered for a real structure exposed to fire in terms of the structural deformation. The structure may fail after the environmental temperature starts to decrease. By comparing the increments of column axial deformations of specimen, it can be found that the heating time significantly affects the column axial deformation occurring in the cooling phase. The longer the heating time, the larger the increments of column axial deformation in the cooling phase. But for beam vertical deformation, the influence of heating time is minor. This may be attributed to the fact that the applied beam load is quite low compared with the column load. However, to clarify this, further research needs to be done.

7. CONCLUSIONS

This paper studied the structural behaviour of eccentrically loaded SRC columns subjected to a fire attack and SRC beam-to-column joint subjected to a fire including heating, cooling and postfire phase. The aim of the research is to obtain the resistance of the SRC column in a beam-column joint during the fire and after the fire. The structural deformation, failure model of SRC columns and SRC beam-column joint were studied in detail considering the influence of major parameters such as the eccentric load, fire duration and steel ratio. The following conclusions can be drawn within the scope of the current studies:

- All specimens showed a typical bending failure in which the concrete in the compression side was crushed and the steel reinforcement yielded in the tension side.
- In the longitudinal direction, the column expanded during the heating phase due to thermal expansion.
- When steel ratio increases, the deformation decreased and time increased.
- When eccentricity increases, the deformation increased and time decreased.
- All the joint specimens failed because of the beam's failure to support the applied beam loads.
- Sixteen models of SRC column specimens with I-sections (ISLB 150, ISLB 175, ISMB 150 and ISMB 175) with different eccentricity (0mm, 45mm, 90mm and 120mm) are analysed in finite element analysis. In the heating phase of composite column, we can conclude that ISMB 175 is better than others from the result of axial deformation versus time.
- Concrete spalling on the SRC columns occurring in the cooling phase was observed during the postfire test. It is reasonable to believe that the presence of external loads in the cooling phase restrained the development of thermal expansion in the interior of the SRC columns and caused spalling of the concrete cover in the cooling phase.
- The postfire experimental results clearly indicate that the increment of column or beam deformation occurring in the cooling phase is much larger than that occurring in the heating phase, which demonstrates the potential failure of SRC joints in the cooling phase.

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