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Fire performance of steel reinforced concrete (SRC) structures

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Abstract

This paper summarizes some of the recent research published on steel reinforced concrete (SRC) structures under or after exposure to fire. The contents include: 1) Fire resistance and post-fire behavior of SRC columns; 2) Fire performance of SRC column to beam joints, by adopting a loading sequence including initial loading, heating, cooling and post-fire loading; 3) Fire resistance and post-fire behavior of SRC composite frames.

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Keywords: Steel reinforced concrete (SRC); Fire safety engineering; Fire peformance; Post-fire

Nomenclature

C	perimeter of the column section (mm)
f	deflection of beam (mm)
f_{cu}	concrete cube compressive strength (MPa)
f_y	strength of steel (MPa)
f_{sb}	strength of reinforcement (MPa)
n	load level in column
N	axial force (kN)
M	moment (kN · m)
R	fire resistance (min)
RSI	residual strength index
T	temperature (°C)
t	fire exposure time (min)
α	steel ratio
β	section depth-to-width
λ	slenderness ratio
ρ	reinforcement ratio
Φ	curvature of section (m^{-1})
θ_r	relative rotation angle of joints (rad)
Δ_c	axial deformation of column (mm)

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1. Introduction

Steel reinforced concrete (SRC) consists of structural steel sections, reinforcing bars and concrete. Such a structural form combines the advantages of both steel and concrete, and thus improves the structural performance at both ambient and elevated temperature. As the concrete, which has much lower heat conduction coefficient, significantly retards and reduces the rise of temperature in the steel sections, the peripheral concrete acts as a sacrificial layer for the steel section under fire. Therefore, it has a high fire resistance in comparison with bare steel structures. SRC members have been widely used in the construction of tall buildings in China at present due to the advantages mentioned previously, as shown in Fig. 1.

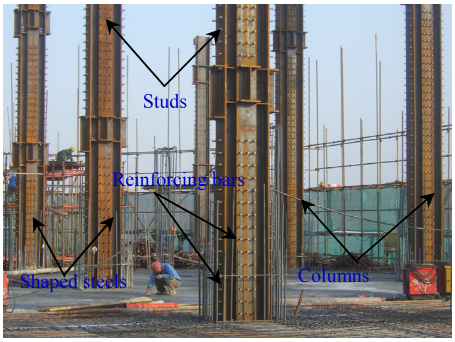


Fig. 1. A general view of a high-rise building with SRC columns under construction.

In the past, there are a large number of published works on the fire resistance of SRC columns [1-5]. Malhotra and Stevens [1] tested fire resistance of 14 encased steel stanchions subjected to axial load ratios ranging from 0.27 to 0.36. Hass [2] tested fire resistance of 40 totally and partially encased steel sections with different cross-sectional sizes, steel sections, concrete strengths and load ratios. Yu et al. [3] tested 12 steel reinforced concrete (SRC) columns with I-steel sections at room and elevated temperatures. Although, the heating fire curves were not followed the specified standard fire curves and the fire resistances of the SRC columns were not obtained, it provided valuable data to verify a proposed finite element analysis (FEA) model. Based on the FEA model, simplified calculation formulae for the ultimate strength of the SRC columns subjected to fire were obtained by a regression analysis. Huang et al. [4] performed a study on the effects of axial restraint on the behavior of composite columns made of encased steel I-sections subjected to fire. Different degrees of axial restraint were applied to the column to simulate its thermal restraint when inserted in a building structure. The columns were tested in an electrical fire resistance furnace and were subjected to an applied load ratio from 0.3 to 0.5 of the design value of the buckling load at room temperature. Moura Correia and Rodrigues [5] tested 12 partially encased steel sections subjected to the ISO 834 standard fire. The influences of load level, axial and rotational restraint ratios and slenderness of the columns were investigated. It is concluded that, for low load levels, the stiffness of the surrounding structure has a major influence on the behavior of the column subjected to fire. However, the same behavior was not observed for the high load levels.

To sum up, fire performance of SRC columns at elevated temperature has been experimentally and numerically investigated before. However, the issues as follows are seldom reported:

- SRC columns with H sections and cross sections under fire.
- Fire performance of SRC column where the load ratio is greater than 0.5 (in the past, the load ratio was less than 0.5).
- Post-fire performance with considering the influence of heating and cooling histories.
- Fire performance of SRC substructures under fire, such as joints and frames.

Set against this background, the fire research group in Tsinghua University has recently been engaged in a series of research projects to investigate the fire and post-fire performance of SRC columns, joints and frames. For the post-fire performance research, a loading sequence including initial loading, heating, cooling and post-fire loading, which is close to the actual fire case, is adopted in the tests and numerical models. The research outcomes are presented and discussed in this paper.

2. Fire resistance of SRC columns

With the purpose of investigating the fire resistance of SRC columns with various section types and load ratio above 0.5, four tests on SRC columns subjected to the ISO 834 standard fire [6] were carried out in 2007 and reported in [7]. The test parameters included steel section type (square section with cross-shaped steel and H-shaped steel), load eccentricity (0 and 75 mm) and load level (0.5 and 0.6). The concrete cube compressive strength (f_{cu}) at fire tests was 38 MPa.

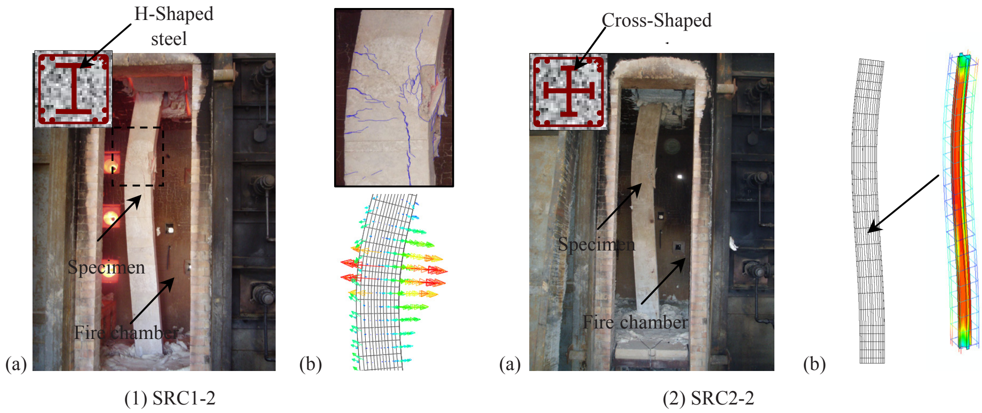


Fig. 2. Typical failure modes of SRC columns in fire. (a) observed; (b) predicted.

The experimental results indicate that the most important parameter that affects fire resistance of SRC columns is load level, and the influence of section type and load eccentricity is moderate. Figs. 2 (a) and (b) show the typical failure mode of the SRC column specimens with H-shaped steel and cross-shaped steel respectively. It is shown that both the tested specimens behaved in a relatively ductile manner until the axial load applied by the hydraulic jack on the column could no longer be maintained and they failed due to the lateral flexural buckling and local concrete crushing in the compression zone. The shaped steel and peripheral concrete can work together very well at high temperature, and the fire resistances of the tested specimens are all above 150 min. The enhanced structural behavior of the columns can be explained in terms of "composite action" between the encased steel and the peripheral concrete. It is expected that compressive stress in the peripheral concrete decrease at the early stage of heating while the temperature of the encased steel section stays at ambient temperature, which transfers additional load onto the core encased steel. The peripheral concrete protects the encased steel from excessive heating and prevents the encased steel from local buckling. In the ultimate limit state, the concrete fails in a brittle manner accompanying with the overall buckling of the encased steel.

Finite element analysis (FEA) model is established to simulate the behavior of SRC column subjected to the ISO 834 standard fire [6]. Simulated results showed that the columns failed due to the deformation of contraction and the rate of contraction which exceeded the failure criteria. Parallel cracks and diagonal cracks were observed in the tension zone at the mid-height zone and spalling was also observed in the compression zone, as shown in Fig. 2. It is also shown in Fig. 2 the predicted plastic strain distributions of the composite column around the lateral buckling zone, where "+" and "-" represent the tension and the compressive strain respectively. It is found that the regions with high plastic tensile strains are generally consistent with the regions where cracks are observed and the regions with high compressive plastic strain are prone to spalling in the fire test. The fire resistances (R) obtained from the FEA model simulation show generally good agreement with those of the measured results, as shown in Fig. 3. This is a reasonable range of accuracy for composite column predictions.

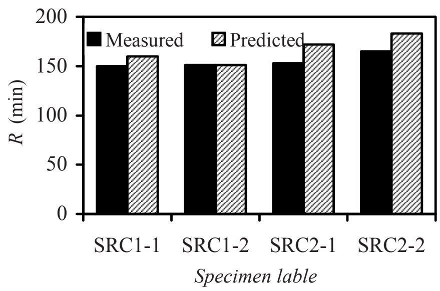


Fig. 3. Comparison of the fire resistance between measured and predicted results.

Based on the FEA model, parametric analysis on the fire performance of SRC columns are conducted and some of the parametric analysis results are shown in Fig. 4, in which residual strength index (*RSI*) is defined as the ratio of the ultimate strength corresponding to the fire duration time (t) to that at ambient temperatures. It is shown that, in general, load level (n), perimeter of column section (C) and slenderness ratio (λ) clearly affect the fire resistance of SRC columns. However, other parameters, such as steel ratio (α), load eccentricity ratio (e/r) and reinforcement ratio (ρ) have a moderate influence, while strength of the concrete (f_{cu}), steel (f_y), reinforcement (f_{sb}) and section depth-to-width (β) have a minor influence. Based on the results of a systematic parametric analysis, a simple formula of fire resistance (R) of SRC column is proposed and has been adopted by the fire resistance design code for concrete building in Guangdong province in China (DBJ/T 15-81-2011) [8].

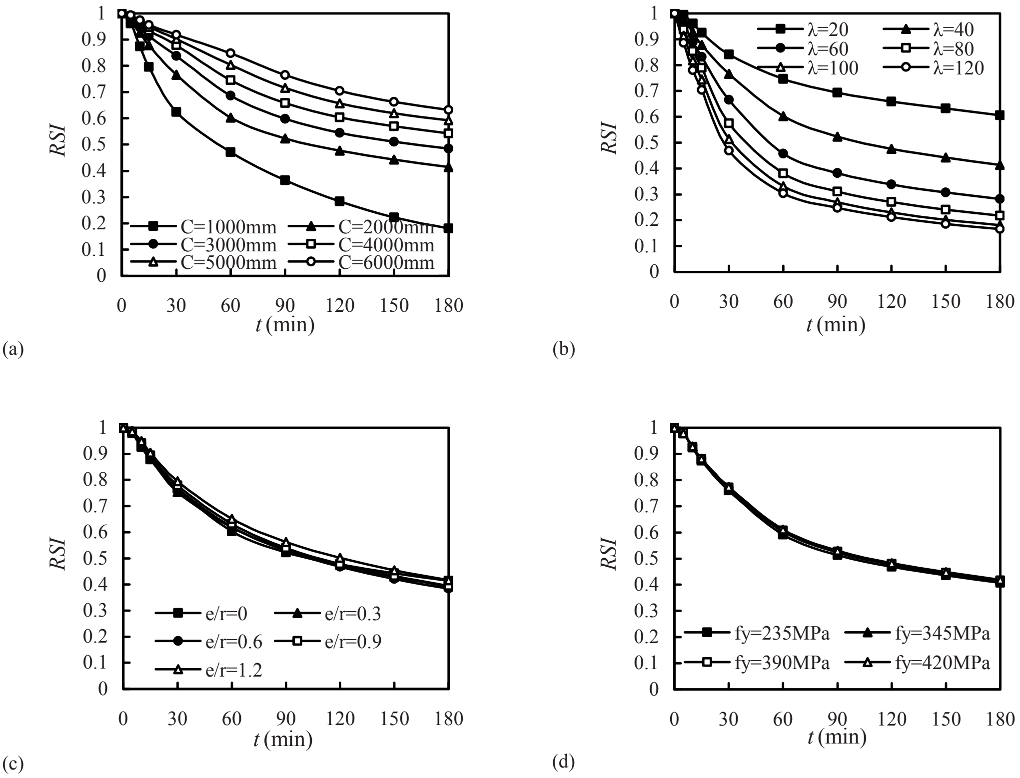


Fig. 4. Residual strength index (*RSI*) versus fire duration time (t) relationship. (a) Diameter (C), (b) Slenderness ratio (λ), (c) Load eccentricity ratio (e/r) and (d) Strength of steel (f_y) (f_y =345 MPa, f_{sb} =335 MPa, f_{cu} =60 MPa, α=4.72%, ρ=0.82%, C=2000 mm, β=1, e/r=0, λ=40)

3. Post-fire behavior of SRC columns

Generally, the process of a real fire includes heating and cooling, and members in a global structure subjected to a real fire are usually damaged to different degrees. Therefore, it is necessary to evaluate the residual strength of a member after exposure to fire, with the purpose of assessing the potential damage caused by fire and establishing an approach for minimum post-fire repair. Accurately quantifying the residual strength depends on the response of members under combined fire and loading corresponding to the real fire. A time (t) - load (N) - temperature (T) loading path of the structure during an entire life-time is proposed in [9], as shown in Fig. 5. The loading path in Fig. 5 includes four phases: 1) Initial loading phase (AB) at ambient temperature (T_o); 2) Heating phase (BC) with constant load (N_o); 3) Cooling phase (CD) with constant load (N_o). The temperature starts to decrease after peak temperature (T_h) at heating time (t_h); 4) Post-fire loading phase (DE). When the temperature drops to ambient temperature (T_o) at time t_d, the load increases until the structure fails at ultimate strength (N_{cr}).

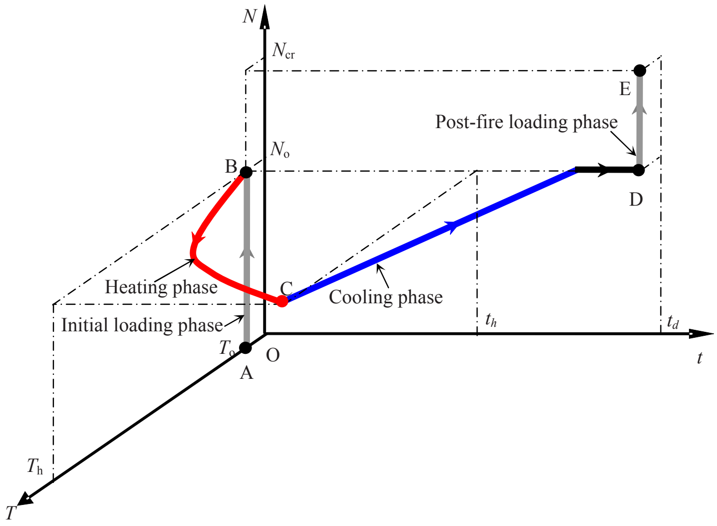


Fig. 5. Time (t) - load (N) - temperature (T) loading path [9].

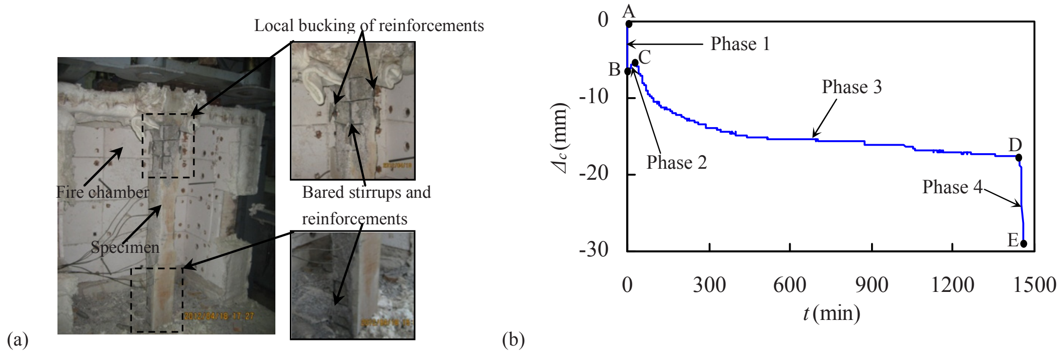


Fig. 6. SRC column fire test based on the t-N-T history (t_h=0.3R, 35 min). (a) Typical failure mode and (b) Axial deformation (Δ_c) versus time (t) relation.

Plenty of research results reveal that in addition to the peak temperature (T_h), the history of loading and temperature is a critical factor to the post-fire performance of structure [9]. Therefore, a full-range analysis considering the t-N-T history as shown in Fig. 5 should be adopted for the post-fire assessment and repair of composite structures. Set against this background, five tests on SRC columns subjected to the ISO 834 standard fire [6] were carried out recently. Three of them were fire resistance tests and the others were post-fire tests based on the t-N-T history shown in Fig. 5. The test parameters include column load level (0.25 and 0.50), heating time (0.3R and R). The average compression cube strength (f_{cu}) for the fire tests was 84.1 MPa with the moisture content of 5.93 %. As a result of the high compactness and low permeability of high strength concrete, fire induced explosive spalling was observed in all the tested SRC columns at the first 12 - 40 min of heating, as shown in Fig. 6 (a). Such spalling has the effect of reducing the cross sectional area of the structural member, and increasing the heat penetration to the exposed steel reinforcement. Thus, spalling might reduce the strength and stiffness of SRC columns, and induces the early failure of them under fire. Compared with the SRC column tests without significant explosive spalling mentioned in Section 2, fire resistance of the three SRC columns are lower than those tests in Section 2 even with the same dimensions, boundary conditions and lower load ratio. Fig. 6 (b) shows the axial deformation (Δ_c) versus time (t) relationship of a post-fire test based on the t-N-T history shown in Fig. 5, in which the axial deformation includes four phases, corresponding to the four phases of the full-range fire path. Increasing the axial load from N_0 to N_{cr} after fire, the SRC column failed due to the local buckling of reinforcement and crushing of concrete at the severest zone of explosive spalling, as shown in Fig. 6 (a).

Currently, besides the above fire tests, the post-fire assessment and repair based on a full-range analysis can be achieved by numerical analysis, and this approach has been introduced in the assessment and repair of the fire-exposed tall building of the Television Culture Centre (TVCC) at CCTV new site [10]. Taking a SRC column in the building as an example, the partially damaged column with fire induced spalling is strengthened by wrapping concrete around the damaged section, called "Increasing Section" method.

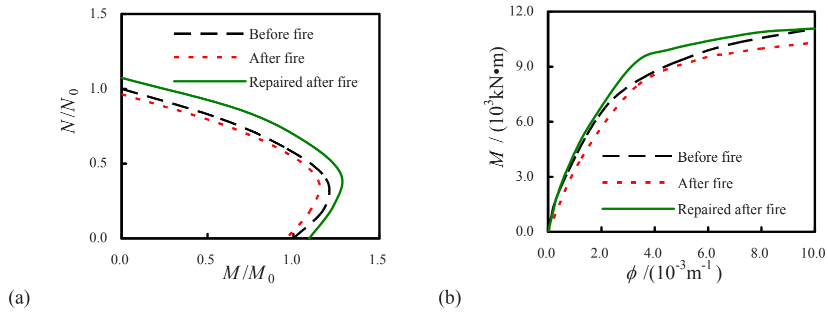


Fig. 7. Post-fire repair and evaluation of SRC columns. (a) N/N_0-M/M_0 curves and (b) M-Φ curves (under pure bending).

Based on the determination of material properties at different phases of the full range analysis, including ambient, heating, cooling and post-fire phases, a FEA model is developed to simulate the behavior of the SRC column under the combined fire and axial load. The N/N_0-M/M_0 and M-Φ relation curves of the SRC column before fire, after fire and repaired after fire are illustrated, as shown in Figs. 7 (a) and (b), respectively, in which, M_0 is the ultimate flexural capacity of the column subjected to pure bending at ambient temperature; N_0 is the ultimate compressive strength of the column subjected to axial load at ambient temperature; M and N are the ultimate flexural capacity and ultimate compressive strength of the column subjected to the combined axial load and bending, respectively; Φ is the curvature of the section. It should be noted that the initial conditions for the SRC column after fire and repaired after fire are different from that before fire, as plastic strain and stress are produced in the section of the column and material performance (strength and elasticity modulus) degrades under the combined fire and axial loading. It is shown in Figs. 7 (a) and (b) that, compared with that before fire, the bearing capacity of the SRC column after exposure to fire decreases, and increases after being repaired.

4. Fire performance and post-fire behavior of SRC substructures

4.1. SRC joints

As the critical element that connects the beam and the column, SRC joints have seldom been researched. Set against this background, two tests of the fire resistance of SRC column to beam joints were performed, as shown in Fig. 8(a) [11]. It was found that the composite joints behaved in a ductile manner, and the tests proceeded in a smooth and controlled way in fire and the failure of the two composite joints were controlled by the left and the right cantilever beams.

Set against the limits of the fire tests, a FEA model was built for the composite joint. The model was verified against the composite joint tests, as shown in Fig. 8(b). Then, a full-size joint that is more representative of real constructions was designed and a FEA model was also built for it. Several primary parameters, such as beam to column linear stiffness ratio, beam load ratio and column load ratio etc., were varied to investigate their influence on the fire resistance and failure mechanism of the composite joints under fire. The following conclusions can be drawn from the parametric analysis: 1) As the columns and beams restrain each other, the internal forces in the composite joints redistribute with the increasing temperature. 2) Beam to column linear stiffness ratio has a significant influence on the fire resistance of the joint. Generally, a weaker beam causes lower fire resistance. 3) Three types of failure modes, including column failed first, beam failed first and beam and column failed together, can occur in fire.

The life-time performance of SRC column to beam joints similar to that shown in Fig. 8 was studied experimentally and analytically by adopting a loading sequence including initial loading, heating, cooling and post-fire loading. Experiments were carried out to obtain both the fire resistance and the post-fire residual resistance of the composite joints. A FEA model was established and verified by the experimental results, and then was used to analyze the temperature distributions and the mechanical characteristics of the composite joints under the combinations of fire and loading, such as stress distributions, internal force and moment versus rotation angle relations [12, 13].

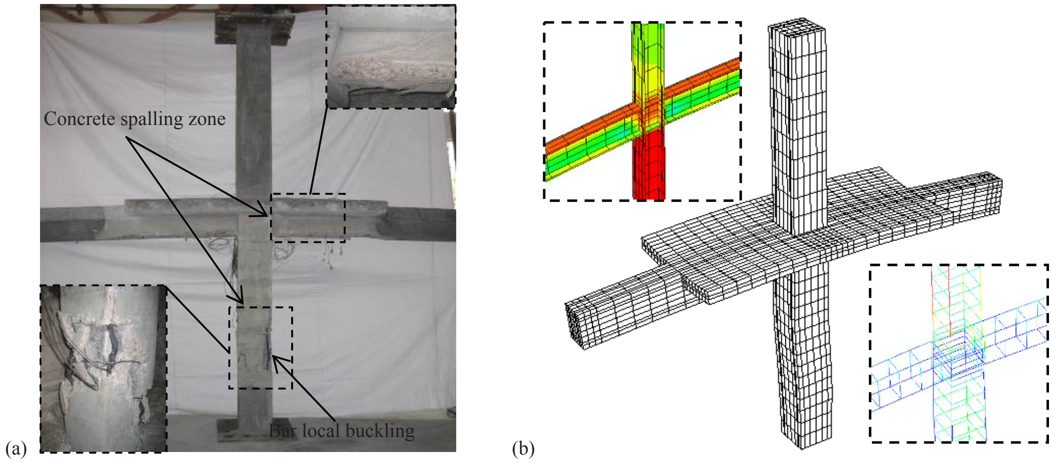


Fig. 8. Failure sketch of SRC column to SRC beam joint in fire. (a) observed; (b) predicted

Based on the FEA model, the influence of various parameters on the moment versus rotation angle relationship of the full-size composite joints with restrained beam are studied, and simplified formulae are proposed to calculate the residual stiffness ratio and residual load bearing capacity ratio of the composite joints. Fig. 9 shows the typical moment (M) versus relative rotation angle (θ_r) curve of the joint in the life-time loading sequence, in which, relative rotation angle (θ_r) designated as the relative rotation angle between beam and upper column; moment (M) designated as the bending moment at the section of beam near to the joint zone. Negative values for moment mean that the relative rotation angle (θ_r) is increasing, while a positive value means decreasing.

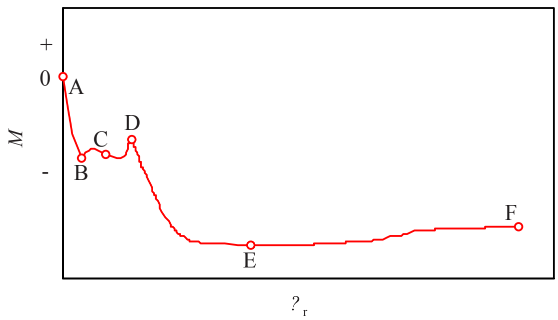


Fig. 9. M-θ_r curve of a full-size SRC column to restrained SRC beam joint.

As shown in Fig. 9, the curve can be divided into four parts:

1) AB is the initial loading phase at ambient. In this phase, θ_r increases with the increase of negative moment;

2) BC is the heating phase with constant beam and column loads. In this phase, θ_r keeps increasing, but negative moment decreases at the beginning of the heating phase and then increases moderately due to the additional moment induced by the thermal expansion of the restrained beam;

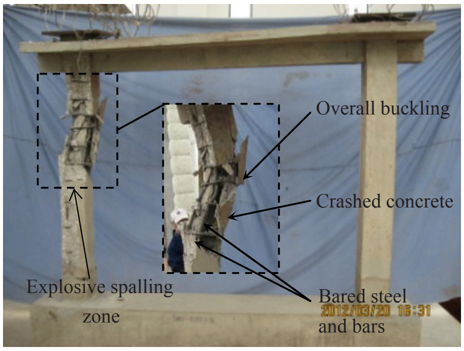
3) CD is the cooling phase with constant beam and column loads. In this phase, the negative moment keeps increasing initially and then starts to decrease due to the cooling contraction of the restrained beam and the redistribution of moment in the beam and column. θ_r still keeps increasing;

4) DEF is the post-fire loading phase. In this phase, keeping the column loads constant and increasing the beam loads, the negative moment increases obviously until getting to the peak point (E). After the peak point, accompanying with the increase of θ_r, the negative moment decreases due to the failure of the joint.

The results of the parametric analysis show that as the beam to column linear stiffness ratio increases, the restraint from beam to column enhances and the ability of the composite joint to rotate reduces, and hence, θ_r at the end of the heating and cooling (the point C and D) diminishes. M at the peak point (E) also diminishes, as the column fails prior to the beam at the post-fire loading phase. Therefore, a proper beam to column linear stiffness ratio is critical for the composite joints under fire in order to achieve the fire safety of the structure.

4.2. SRC portal frames

It is well known that structural members in a framed structure behave differently from isolated members with simplified boundary conditions at both ends, as structural continuity imposes a finite amount of restraint to the adjacent and connected component. Similar to the post-fire behavior tests of SRC columns and joints, the life-time performance of SRC planar frames, is also studied by adopting a loading sequence including initial loading, heating, cooling and post-fire loading. Seven tests on SRC columns to reinforced concrete (RC) beam portal frames and three tests on SRC columns to SRC beam portal frames subjected to the ISO 834 standard fire [6] were carried out recently, in which four of them were fire resistance tests and the others were post-fire tests based on the *t-N-T* loading path shown in Fig. 5. Based on the fire resistance test results, the heating times (t_h) for post-fire tests were decided to make sure that the post-fire test specimens could survive from the heating and cooling phases. The test parameters included load level in column (0.25 and 0.50), heating time (0.3R, 0.6R and R) and beam to column linear stiffness ratio (0.36 and 0.77). The average compression cube strength (f_{cu}) and the moisture content at the time of the fire tests were 65.6 MPa and 5.42 %, respectively.

(a)


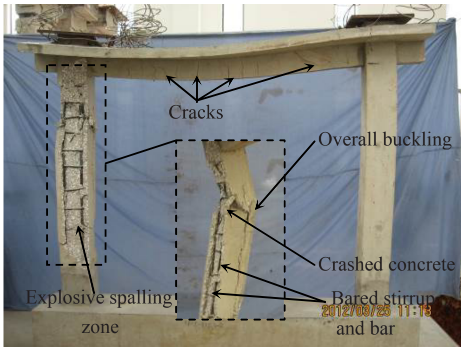
(b)


Fig. 10. Failure mode of SRC column to RC beam portal frame in fire (fire resistance tests). (a) column failed (t_h=R, 75 min) and (b) beam and column failed together (t_h=R, 140 min).

The main results are as follows:

1) Fire induced explosive spalling was observed in the SRC columns in the first 12-40 min of heating, which was not observed in the RC and SRC beams, as the hot steam pressure was released though the tensional cracks.
2) For the fire resistance tests, the SRC columns failed at elevated temperature as severe explosive spalling occurred in one of the two columns, two types of failure modes at elevated temperature were observed. One mode was that the column failed and the other was the beam and column failure together, as shown in Figs. 10 (a) and (b), respectively. Out-of-plane overall buckling of the failed column was observed for the both failure modes. For the former failure mode, as shown in Fig. 10 (a), mid-span deflection of the beam was minor, and no obvious cracks were observed at the bottom section of the beam. The frame failed due to the sudden collapse of the column. For the latter failure mode, a large number of cracks distributed around the mid-span of beam were formed, as shown in Fig. 10 (b). The failure of the frame was controlled by the failure of the beam and the column together. The above-mentioned results are somewhat different with that of concrete filled steel tubular (CFST) column to RC beam portal frames in [14, 15], in which deformations of the two CFST columns were coincident without obvious explosive spalling and two types of failure modes, including failure mode I (columns failed first) and failure mode II (beam failed first), are introduced.

3) For the post-fire tests, keep the loads on the columns constant and increase the loads on the beam continuously until the frames failed. As the heating time (t_h) was 0.3 or 0.6 times that of the tested fire resistance (R), the SRC column kept integrity at heating and cooling although explosive spalling occurred in the SRC column. Two types of failure modes for the post-fire tests were observed. One is the beam failed first, and the other is the beam and column failed together, as shown in Figs. 11 (a) and (b). The failure modes of post-fire tests are somewhat different to those of the fire resistance tests, as only the beam load is prescribed to increases for the post-fire loading, which leads to the failure of the frame being controlled by the failure of the beam.
4) It is found that the fire resistance of SRC frames decreases as the column load ratio increases, however, for the post-fire tests, the residual strength of the frame is mainly controlled by the beam, therefore, the column load ratio has a minor influence on the post-fire residual strength of the frame.

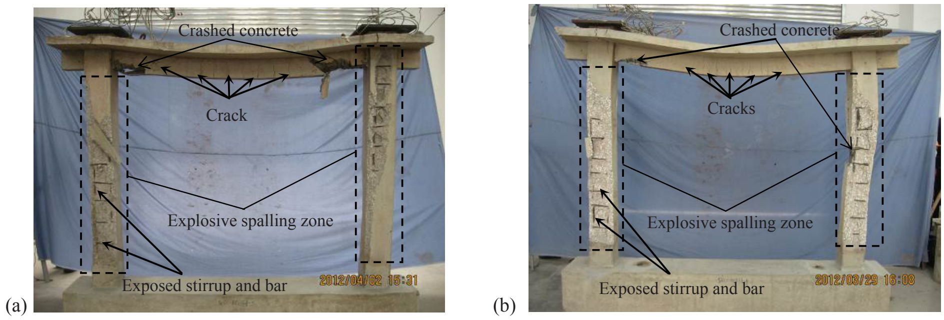


Fig. 11. Typical failure modes of SRC column to RC beam portal frames in full-range fire (post-fire tests). (a) beam failed (t_h=0.3R, 45 min) and (b) beam and column failed together (t_h=0.6R, 85 min)

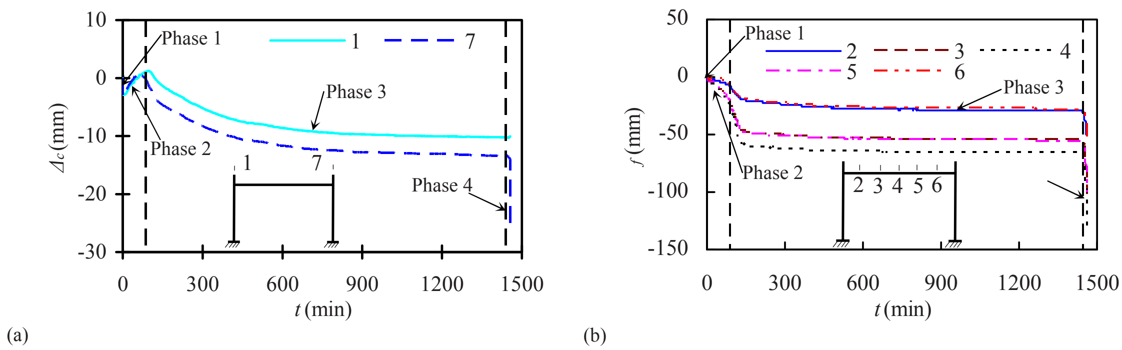


Fig. 12. Δ_c - t and f- t relationship of SRC column to RC beam planar frames in full-range fire. (a) column axial deformation (Δ_c) - time (t) relationship and (b) beam deflection (f) - time (t) relationship

Taking the frame specimen where the beam and column failed together as an example, Figs. 12(a) and (b) shows the measured column axial deformation (Δ_c) versus time (t) and beam deflection (f) versus time (t) relationship over the entire loading phase, respectively. These curves can be divided into four phases just like the curve in Fig. 6 (b), and the following characteristics can be found:

1) Initial loading phase (Phase 1). The column axial deformation and beam deflection increase with the increasing of external loads.
2) Heating phase (Phase 2). The columns experience an expansion stage due to the effect of thermal expansion at the beginning of heating phase, and then, as the temperature increases, the contraction due to the material properties degrading becomes dominant. The beam deflection keeps increasing continuously due to the material properties degradation.
3) Cooling phase (Phase 3). At the beginning of the cooling phase, the column axial deformation and beam deflection keep increasing due to the reduced frame bearing capacity induced by the heated internal materials. After 10 hours of cooling, the further deformation of the frame is minimal.

4) Post-fire loading phase (Phase 4). The temperature of the frame drops to normal temperature after 24 hours of cooling. Then, the beam load increases with constant column loads until one of the two columns and the beam fail together.

5. Conclusions

Some recent research work on the fire resistance and post-fire performance of typical SRC structures, including SRC columns, SRC column to SRC beam joints and SRC composite portal frames with RC and SRC beams, are presented in this paper. The results show that SRC structures behave in a ductile manner under and after fire, and have excellent fire performance because of the "composite action" between the encased steel and the peripheral concrete.

Several research needs on the fire performance of SRC structures should be noted for the future, which are listed as follows: (1) For the post-fire performance research of SRC structures, research should focus on load and temperature histories; (2) With regard to material performance during the cooling and post-fire phases, the importance of the constituent materials such as concrete and steel at elevated temperature has been highlighted. However, material property data in the cooling and post-fire phases are scarce, which will limit the post-fire assessment and repair based on full-range analysis. (3) Currently, high strength concrete (HSC) has been used in real SRC structures, but the related fire research on SRC structure with HSC is limited. HSC is likely to undergo explosive spalling under fire condition, which induces the fire performance of SRC structure with HSC is different from the SRC structure with normal strength concrete. Therefore, it's imperative to perform further research on the fire performance of SRC structure with HSC. (4) For global structures in fire, the fire resistance of substructures is different from that of the constituent single members due to their interaction under fire. Therefore, the research based on single members should be forwarded into substructures or global structures the research outcome close to the real behavior of building in fire.

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