

Fire resistance of concrete-filled steel tube columns with preload. Part I: Experimental Investigation

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Abstract: Preload in a cast-in-situ concrete-filled steel tube (CFST) structure is an important parameter that has been studied and considered in design and construction. However, the impact of a preload on fire resistance of CFST has not been taken into account in the existing design method of CFST under fire. In this paper, twelve CFST columns with and without preload in the steel tubes are experimentally studied to investigate their heating process, failure modes, thermal and structural responses. The test results show that preload of the steel tube has significant impact on the fire resistance of some of the columns. Further investigations on this important observation will be done numerically in a companion paper^[24] to carry out a more comprehensive parametric study.

Keywords: Concrete-filled steel tube (CFST); Preload; Fire resistance; experimental study

Notations

A_s, A_c	area of steel and concrete, respectively
f_y	characteristic strength of steel tube
f_{cu}	ultimate compressive strength of concrete
N_t	total axial load applied to column
N_{pre}	preload applied to steel tube
N_{add}	additional load to column
N_0	characteristic plastic resistance of CFST column, $N_0 = A_s f_y + A_c f_{cu}$
U	vertical displacements
r	load ratio
β	preload ratio, $\beta = N_{pre} / \varphi_s N_{0,s}$
D	diameter of steel tube
d_s	thickness of steel tube
H	height of specimen

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1. Instruction

Concrete-filled steel tubular (CFST) structures not only have good static and seismic performance, but also can make full use of the stiffness and load bearing capacity of the hollow steel tube during the process of concrete casting to allow faster construction. This is one of the main reasons for their rapid development and wide applications in tall and super high-rise buildings. In recent years, there have been increased research demands on fire resistance of such structures, especially in relation to applications of high-rise buildings.

Extensive theoretical, experimental and numerical researches on CFST structures under fire have been carried out and reported in the literature. In terms of theoretical studies, various design formulas and calculation methods of CFST structures under fire have been proposed by Kodur, et al.^[1,2], Tan^[3], Yu^[4]. Using numerical techniques, Yang^[5], Lie, et al^[6] and Yu, et al^[7] carried out investigations on fire-resistance of CFST. The most convincing approach to study the behavior of CFST under fire is by experimental studies. Many researchers, e.g., Lie and Chabot^[8,9], Meichun^[10], Okada^[11], Sakumoto^[12], Moliner, et al^[13] and Han^[14], carried out experimental investigations on the behavior of CFST structures and made significant contributions to the subject. Their experiments studied a range of critical design parameters, including support conditions, section profiles, type of concrete, type of steel tubes and load ratios. However, most of the investigations were exclusively on testing the structures after they had been made and were fully functional as integrated units of a structural system with little consideration of the effect of preload induced in the construction process.

Due to the advances in experimental and modelling techniques, it is possible now to test and simulate structures subjected to more realistic loading scenario, including any preload developed during the course of continuous construction^[15,16], as well as the preload resulted from shrinkage and creep of concrete^[17]. Since preload may have significant influences on the behavior of CFST structures, many researchers, e.g. Zha^[18], Han^[19], Huang^[20], Patel^[21] and Liew^[22], carried out extensive theoretical and experimental investigations on the effect of preload on CFST structures at room temperature. For example, Liew et al^[22] proposed formulas for calculating stability factor of preloaded columns by considering preload as an equivalent form of initial bending denoted by a preload influence factor and the formulas were given on the basis of the Eurocode 4 formulas without preload. Han^[19] pointed out that the existence of preload would make the bearing capacity of a CFST structure reduced by up to 20% in a practical design. However, the existing fire-resistance design methods in the codes of practice of CFST structures ignore the effect of preload in steel tube, which may result in an over estimated fire-resistance time.

To the authors' best knowledge, there is no fire-resistance experiments on preloaded CFST reported in the literature. In order to fill the research gap, this paper presents fire-resistance experiments on 12 full-scale CFST columns with and without preload. During the tests, temperature, deformations, failure modes and fire-resistance times of the columns were recorded to study the influence of preload on their fire-resistance performance.

2. Experimental study

2.1 Test specimens

All 12 tested CFST circular columns have a diameter of 219mm. The thickness of the steel tube is 4.0 mm. The columns are 3470 mm long from the top to the bottom ends with a slenderness

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of 63.4. The columns were tested when they were subjected to various preloads and additional loads. The test parameters include preload ratio, β , which is the ratio of the preload to the characteristic buckling resistance of the steel tube, and load ratio, r , which is the ratio of the total axial load to the characteristic plastic resistance of the CFST column. The total axial load N_t includes the preload N_{pre} plus the additional load N_{add} , namely, $N_t = N_{pre} + N_{add}$. Four levels of pre-loads, i.e., $\beta = 0, 0.2, 0.4$ and 0.5 and three levels of the total axial loads i.e., $r = 0.3, 0.5$ and 0.7 , are considered. The columns are labeled by C_{ij} , where the 1st number, i , denotes the level of total load ratio, and the 2nd number, j , indicates the level of preload. The full details of the columns and loads are listed in Table 1.

Table 1 Parameters of CFST columns with preload

Specimen ID	Steel tube dimensions $D \times d_s \times H$ (mm)	f_y /MPa	f_{cu} /MPa	Preload ratio, β	Preload N_{pre} /KN	Load ratio, r	Total load N_t /KN
C11	219×4.0×3470	320	33.1	0	0	0.3	395.5
C12	219×4.0×3470	320	33.1	0.2	145.4	0.3	395.5
C13	219×4.0×3470	320	33.1	0.4	290.8	0.3	395.5
C14	219×4.0×3470	320	33.1	0.5	363.6	0.3	395.5
C21	219×4.0×3470	320	33.1	0	0	0.5	659.2
C22	219×4.0×3470	320	33.1	0.2	145.4	0.5	659.2
C23	219×4.0×3470	320	33.1	0.4	290.8	0.5	659.2
C24	219×4.0×3470	320	33.1	0.5	363.6	0.5	659.2
C31	219×4.0×3470	320	33.1	0	0	0.7	922.9
C32	219×4.0×3470	320	33.1	0.2	145.4	0.7	922.9
C33	219×4.0×3470	320	33.1	0.4	290.8	0.7	922.9
C34	219×4.0×3470	320	33.1	0.5	363.6	0.7	922.9

Note: The total loads are determined from the load ratio and the characteristic plastic resistance of the CFST column; the preloads are calculated on the basis of the preload ratio and the characteristic buckling load of the steel tube.

The geometry and top view of the column are shown in Figure 1(a) and (b), respectively. Two 20 mm thick end-plates were welded, respectively, to the ends of the steel tubes, which made the total column length 3430 mm. The steel plate at the top end has a central through-hole of 100mm in diameter (for pouring concrete). Four through-holes of 32mm in diameter (installing bolts) were drilled on both plates to allow installation of 4 pre-stressing rods to apply the preload. Desired preload in the steel tube was applied by tightening the bolts at the top ends of the rods. Rib stiffeners were mounted on the external wall at the ends of the column to provide additional stability. The two circular holes of 20 mm in diameter located below the rib stiffeners at the top end provided ventilations to release water vapor pressure developed during the experiments.

The specimens and the process of pouring concrete are shown in Figure 1(c) and (d), respectively. The columns were placed in an upright position and filled with concrete. An internal vibrator was then used to consolidate the concrete inside the columns. The columns were left upright for 28 days before being stored horizontally at room temperature until they were tested. Five material coupon tests were carried out to determine the properties of the steel tubes, which gave an average yield strength of 321.6MPa and an average Young's modulus of 2.04 GPa. Six standard concrete cubes (150mm×150mm×150mm) were made from the concrete taken when they were casting into the steel tube to determine the properties of the concrete. The concrete cubes were tested at an age of 28 days, giving an average compressive cube strength (f_{cu}) of 27.3 MPa. The average compressive cube strengths (f_{cu}) at the day of fire tests was 33.1 MPa.

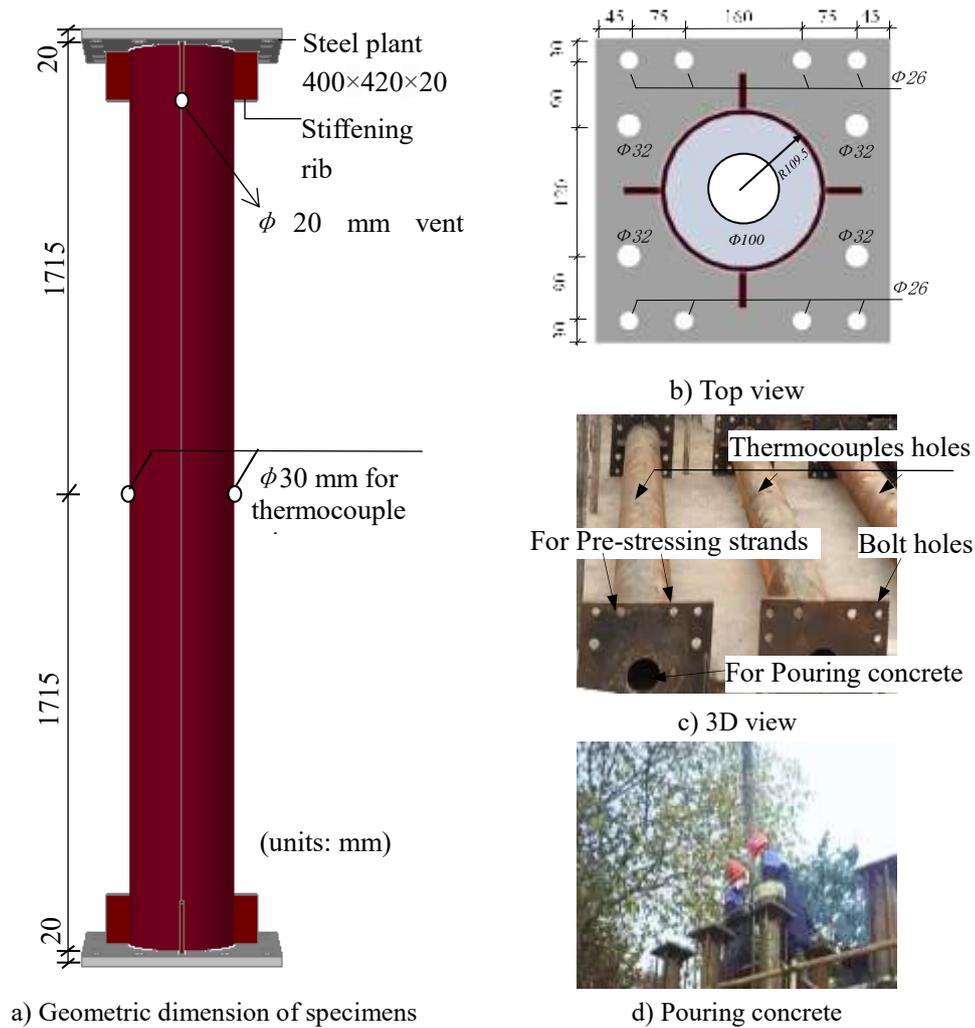


Figure 1 Geometry and manufacturing process of specimen

As shown in Figure 2, two small holes of 30mm in diameter located at the middle of the steel tube (Figure 2b) provided entry of 4 type K (chromel-alumel) thermocouples that were used to measure the temperature of the concrete at the 4 locations of the cross-section shown in Figure 2(a). The holes were filled and sealed with grouting materials that have similar properties to the concrete. A type K thermocouple was also fixed at the surface of the steel tube as shown in Figure 2(c) to measure the surface temperature of the column.

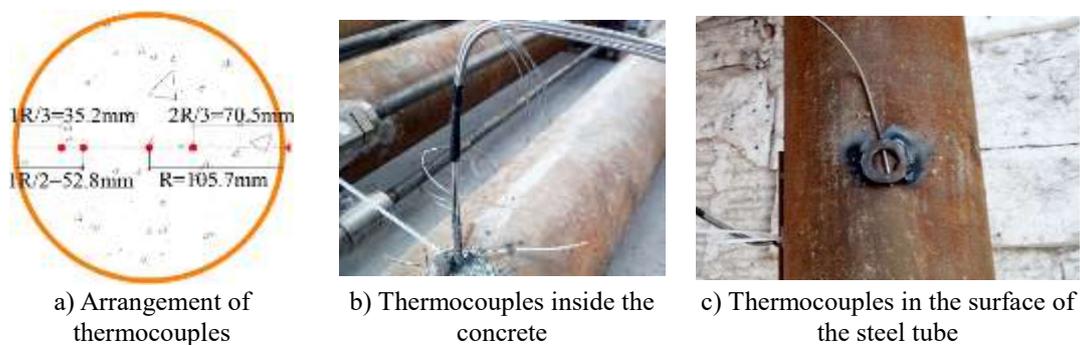


Figure 2. Arrangement of thermocouples

2.2 Preloading the steel tube

A self-balancing test device was adopted to preload the steel tube before pouring concrete. A schematic diagram of the preloading rig is shown in Figure 3a, which consists of the column to be preloaded and four pre-stressing rods. As shown in Figure 3b and 3c, prior to setting the columns upright, the 4 steel rods were mounted to connect the two end plates so that preload could be applied to the column by tightening the bolts at the ends. After the bolts were tightened, the end-plates showed some visible bending deformation as shown in Figure 3c. However, this deformation does not affect the forces transferred to the column, thus will not affect the test results. The level of the preload was monitored by the force sensors mounted on the middle of the rods.

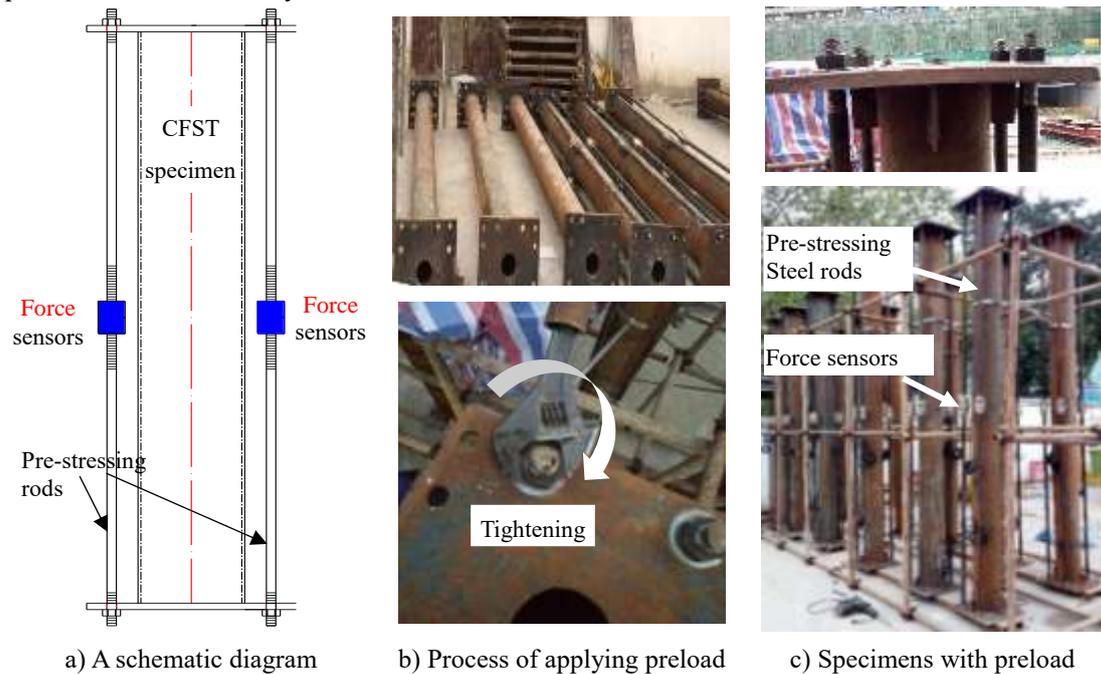


Figure 3. Setup and process of applying preload

The columns were then set upright and the preload was closely monitored to ensure that it was not reduced at least in the next 72 hours. The levels of the preload imposed on the steel tubes are specified in Table 1.

2.3 Test conditions and procedure

The fire tests were carried out using a multi-functional fire test furnace at Jiangsu Key Laboratory of Structural Engineering (JKLSE) in China. It was specially designed and built for testing structure members, such as columns, walls and slabs subjected to fire. The furnace consists of a heating chamber (insulated with fireproof fibers), an automatic fire control system, loading apparatus, a data collection system, high temperature camera device and displacement acquisition equipment.

The furnace is capable of simulating temperatures up to 1200 °C and has a maximum loading capacity of 5000kN. During the test, the temperature inside the furnace was automatically or manually controlled to follow the ISO-834 standard fire curve. More details of the test set-up are shown in Figure 4. The columns were pinned at the two ends. The axial load was applied to the CFST columns by a hydraulic jack located at the top of the furnace chamber. The vertical displacement of the top end of the CFST was captured by displacement transducers. The entire

heating process was monitored by the fire-proof camera system.

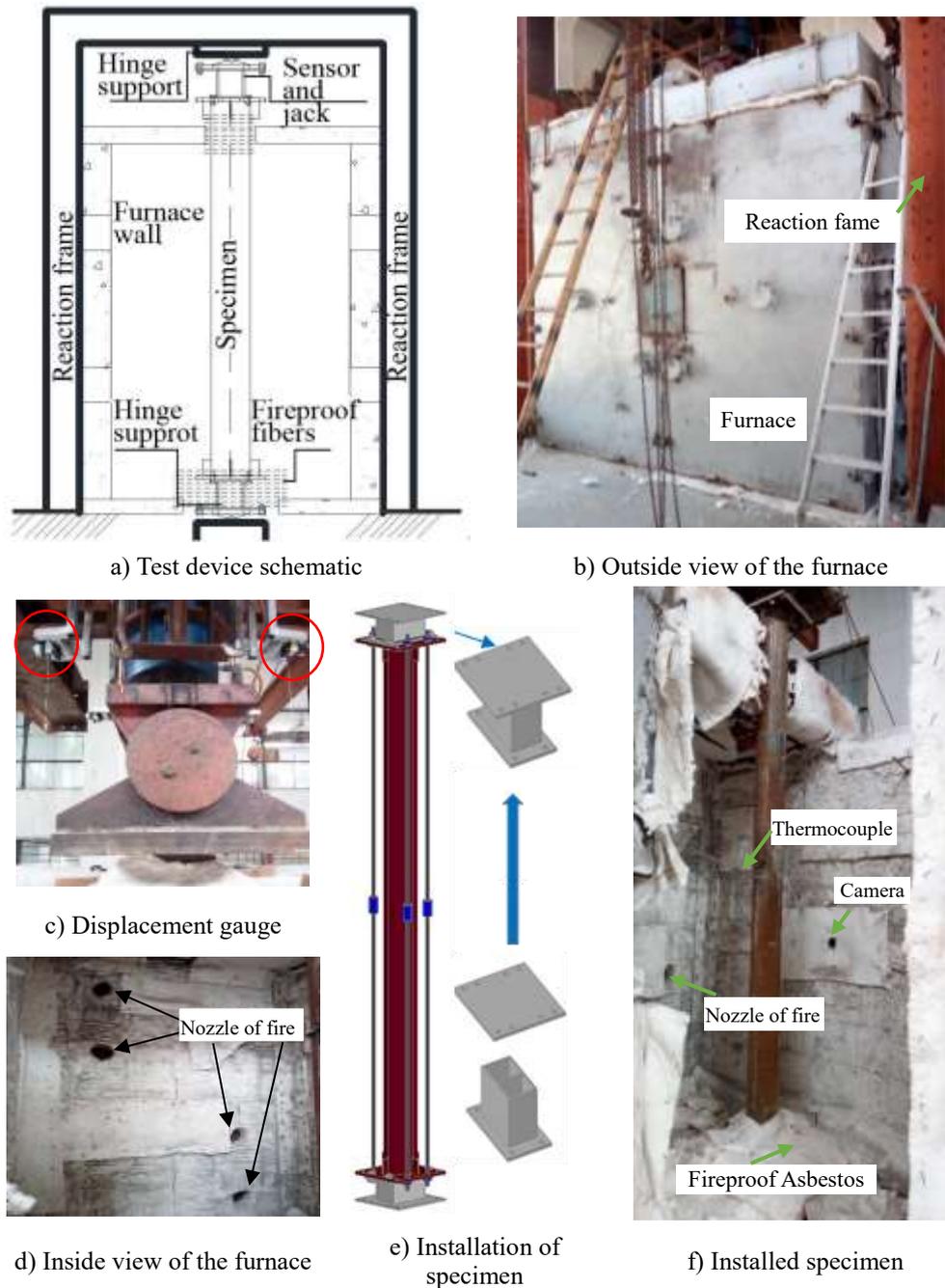


Figure 4 Test set-up and instruments

The ambient temperature at the start of each test was approximately 20°C. During the test, the column was exposed to controlled heat such that the average temperature in the furnace followed as closely as possible the ISO-834 standard temperature-time curve.

The tests have the following main steps.

- 1) Install the columns between the supports at both ends to ensure that eccentricity of the axial force is ignorable.
- 2) Remove the 4 pre-stressing rods while, at the same time, make sure that the force from the hydraulic jack is sufficient to maintain the preload in the steel tube.

- 3) Apply multi-step loads using the programmed hydraulic jack and measure the vertical displacement at the top of the column to test if the displacement transducers are working properly.
- 4) Heat the furnace by following the ISO-834 standard temperature-time curve.
- 5) Terminate the test when excessive deformation or sudden loss of load bearing capacity of the column is observed.

3. Results and discussion

3.1 Heating process and failure modes

In order to observe the deformation of the CFST columns during fire, a high-temperature camera was used to record the entire heating process inside the furnace. Figure 5 shows the heating process of column C11. The deformation of the column was not obvious until 30 minutes after ignition. The column started to show visible bending that became more obvious at 47 minutes. Eventually the column collapsed suddenly due to loss of its load bearing capacity. Similar observations were made from other tested columns.

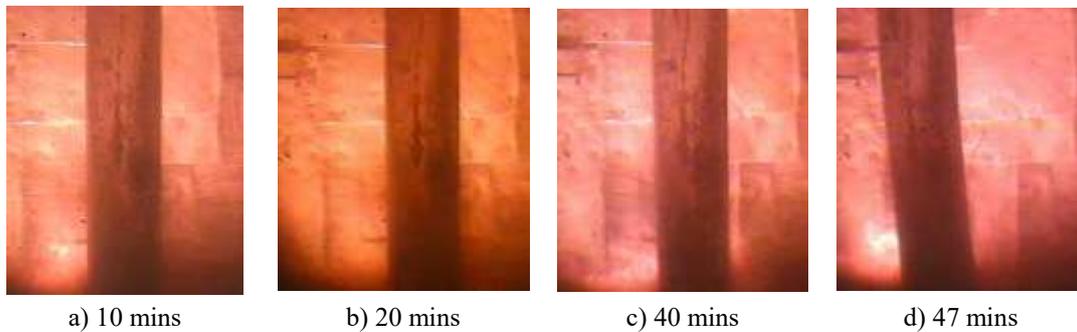
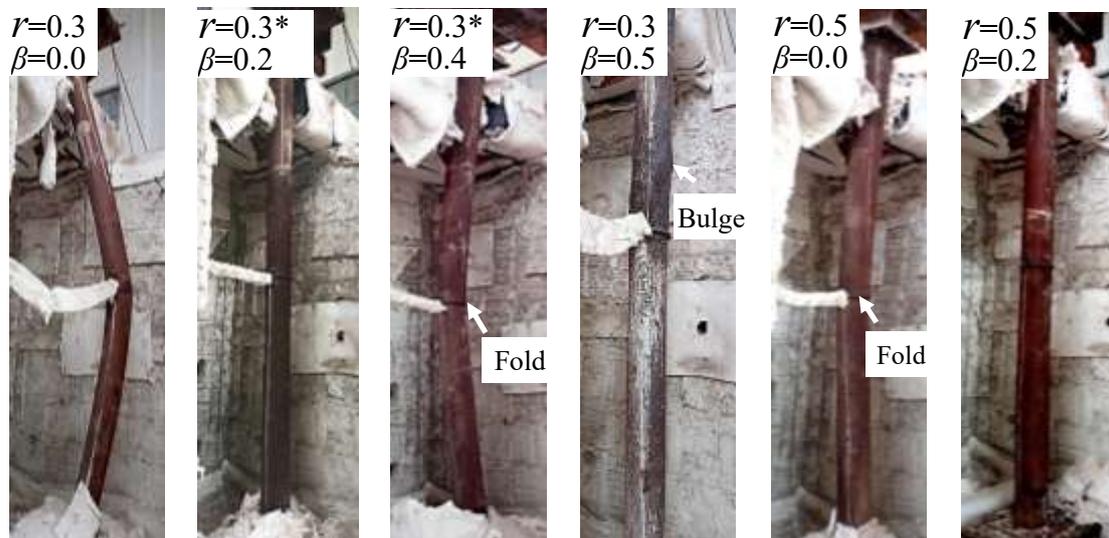


Figure 5. Experimental process of C11

Figure 6 shows the failure modes of all the columns after the fire tests. Evidently, overall buckling is the dominating failure model, though local folding and bulging occurred to some of them. It was obvious that a higher load level always resulted in a greater bending deformation. From the test results, it is shown that both the load ratio and preload ratio have little impact on the failure mode of the CFST columns.



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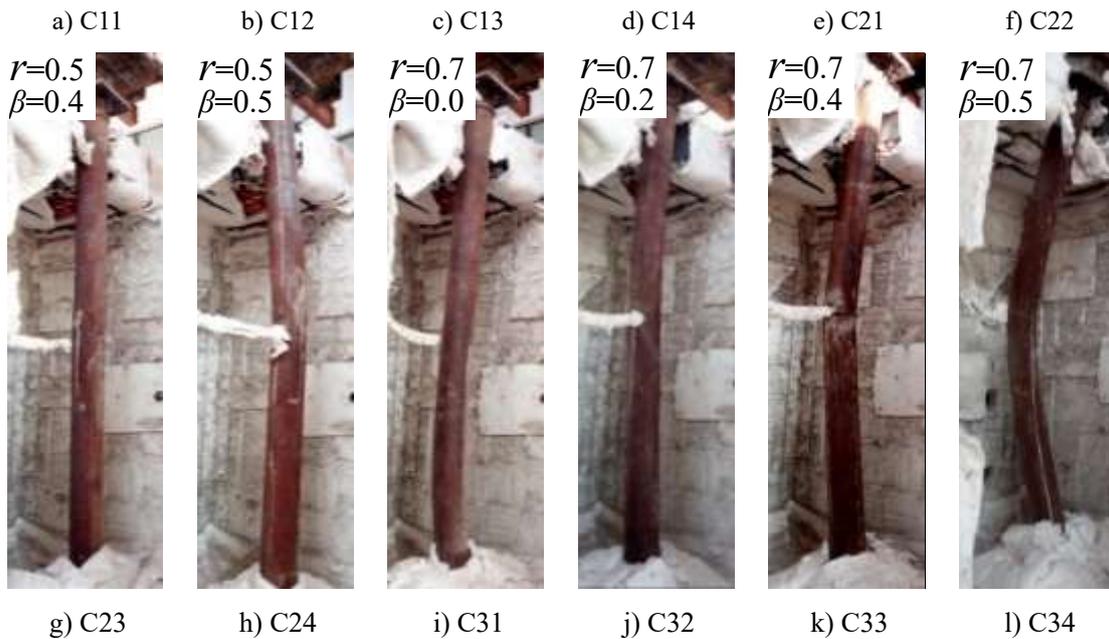
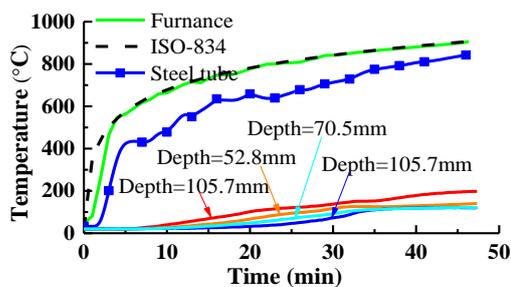


Figure 6 Failure modes of specimens after tests

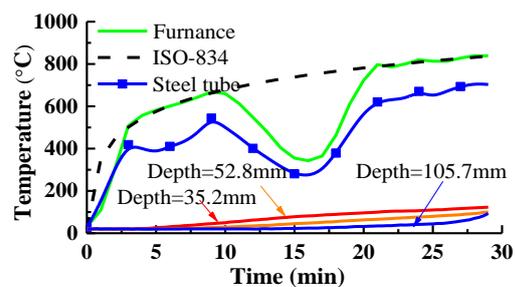
It is worthwhile to mention that due to some technical issues, the total axial load ratios of C12 and C13 were not successfully achieved during the test, which is denoted in Fig. 6 using an asterisk against their respective designed total load ratios.

3.2 Thermal response

Figure 7 shows the time-dependent temperature field in the furnace and at various locations of the columns. The temperature in the furnace follows well the ISO-834 standard fire curve. The temperature of the steel tube is lower but generally follows the trend. The temperature of C12 shows significant fluctuation that was attributed to the unstable fuel supplies occurred during this particular test. In general, temperature is gradually reduced from the surface of steel tube to the center of the concrete core. It can also be observed that the heating rate and temperature gradient are decreasing toward the center of the concrete section. The rate of temperature rise in the concrete core becomes smaller when the temperature is about 100°C due to evaporation of water in the concrete, which consumes a significant amount of thermal energy. This phenomenon is termed ‘temperature plateau effect’, and is more obvious towards the center of the concrete core. After the temperature plateau, an acceleration of temperature rise is observed. However, this effect can be seen only in C11 and C14 since the concrete temperature of other columns did not reach 100°C .



a) C11 columns with $r = 0.3, \beta = 0.0$



b) C12 columns with $r = 0.3^*, \beta = 0.2$

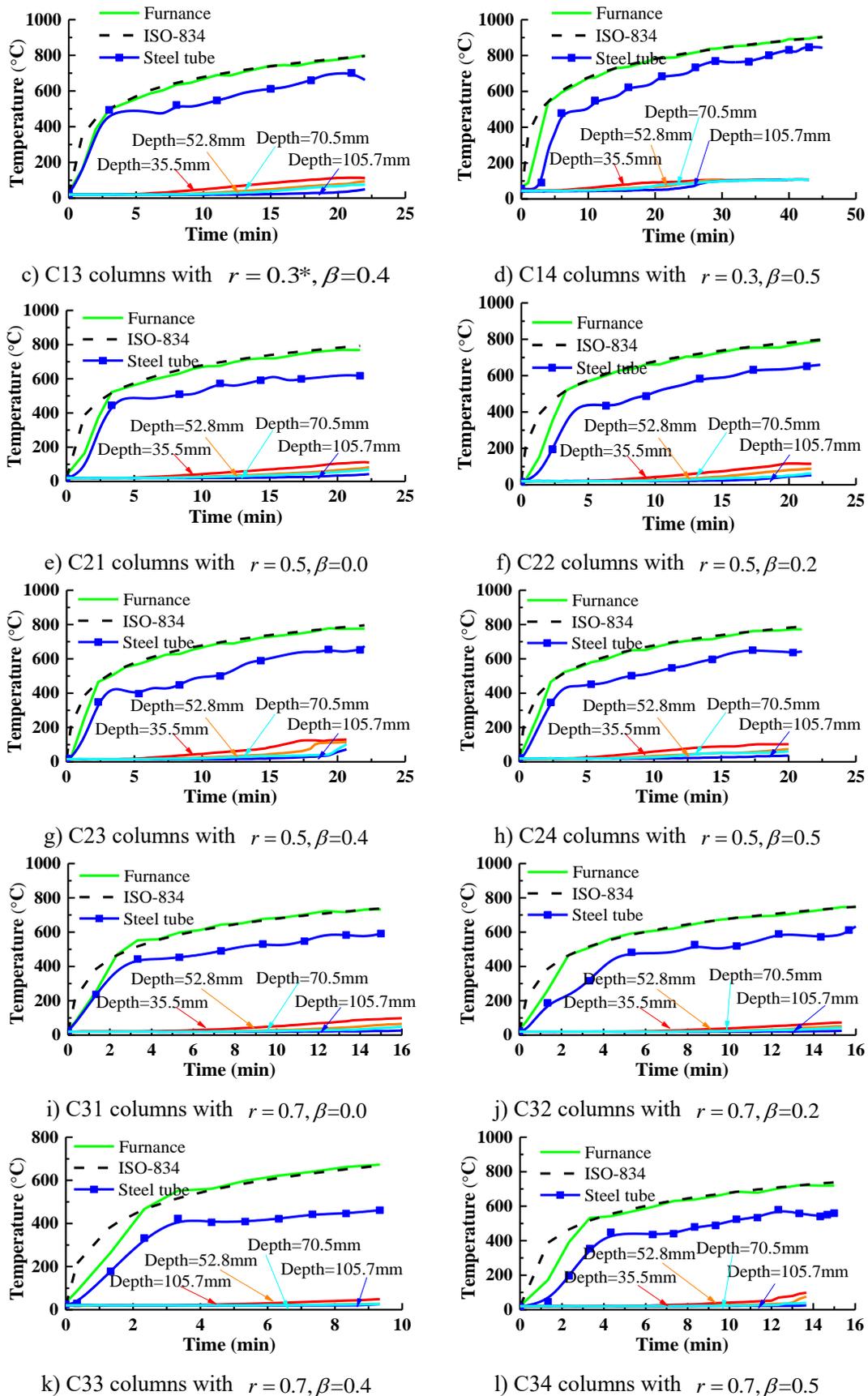


Figure 7. Measured temperatures as a function of time at various depths in the CFST columns.

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Figure 8 compares the temperature at the 4 locations (see Fig.2a) of the concrete core for all the 12 tested columns. It can be seen that there is no significant temperature difference across all the 12 columns except C14. The observed discrepancy of C14 was due to an unexpected heating disruption occurred when the temperature reached about 68°C. The heating process was restarted without waiting until the furnace was cooled down to the room temperature. Nevertheless, the results in Figure 8 are sufficient to illustrate that both the preload and the total axial loads have no significant influence on the temperature field of the concrete core.

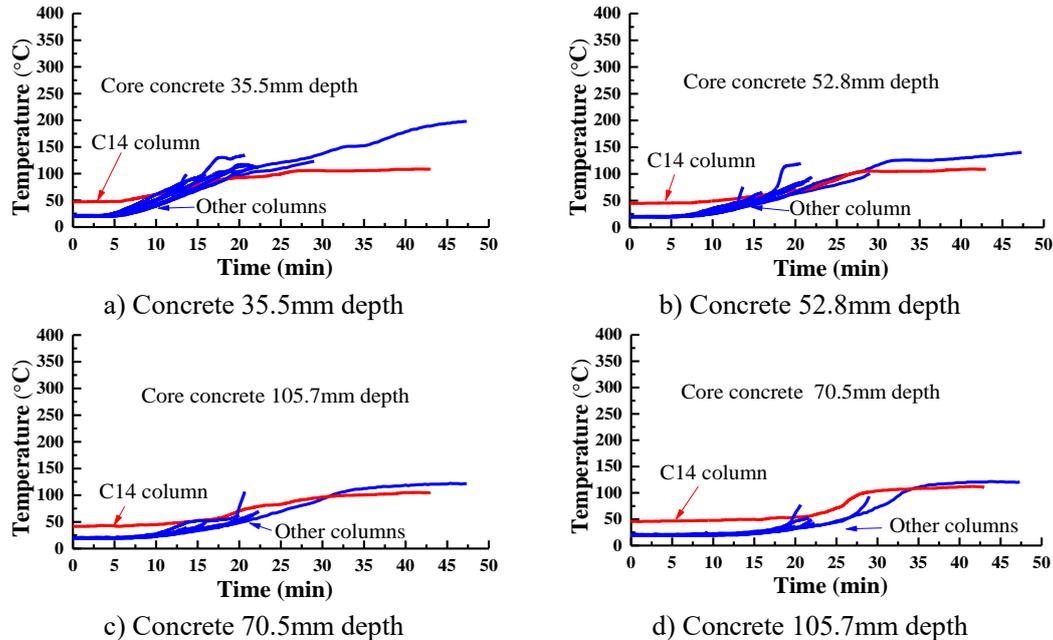
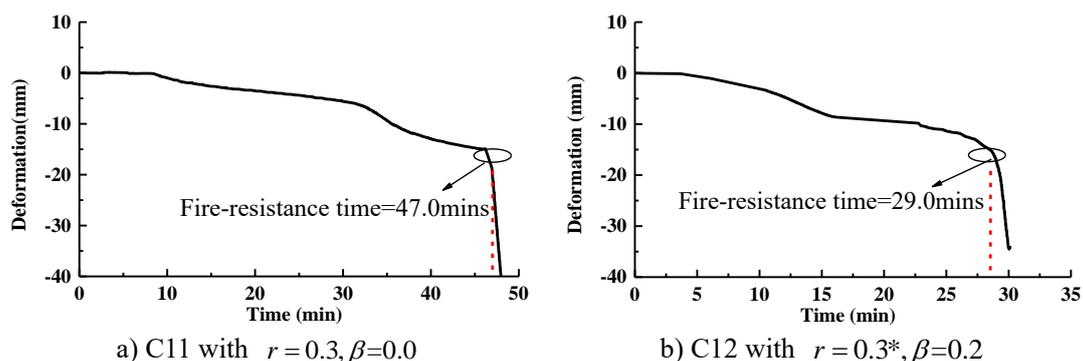


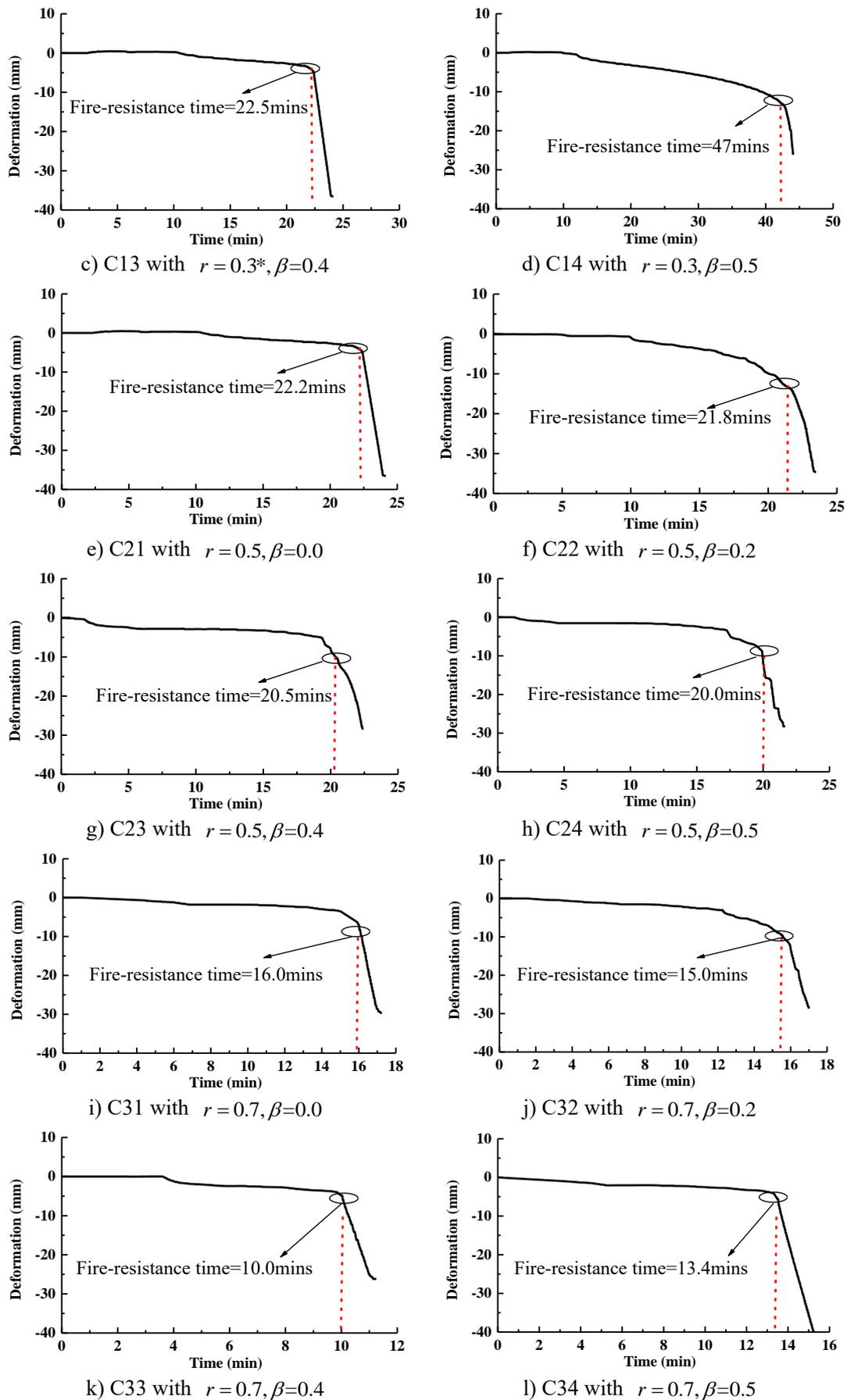
Figure 8 Measured temperatures as a function of time at various depths of the concrete

3.3 Structural response

The vertical displacements, U , at the top ends of the columns are plotted versus time and shown in Figure 9. The vertical deformation of the top end consists of compressive axial compression due to the axial load and thermal expansion resulting from the elevated temperature. At the beginning of the test, thermal expansion is greater than the compressive deformation resulting in a rather flat curve as the upwards motion of the top end is restrained by the hoisting jack. After this stage, the curve starts to decline as the compressive deformation caused by the axial compression gradually overtook the thermal expansion when the temperature continuously rose. The temperature softening effect of the steel tube is obvious when the temperature reaches 600°C, when concrete crushing occurs and the CFST columns loss bearing capacities.



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Figure 9. Top end vertical displacement U versus time t

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A review of the measured displacements plotted in Figure 9 indicates that both the total load and preload ratios have significant influence on the vertical displacements of the top ends. For the columns with the same preload ratios, e.g., C11, C21, C31, a higher total load (including additional load and the preload) always results in a greater axial displacement. The same correlation applied to the columns with the same total load, i.e. C21, C22, C23, C24, a higher preload ratio also results in a greater axial displacement, which is attributed to the higher stresses in the steel tube at the earlier stage of the loading process. Furthermore, lateral deflection of the columns with preload is larger than that of the columns without preload. The steel tubes of the columns with a higher preload will yield earlier when they are exposed to fire, which will reduce the bearing capacity of the columns subjected to axial compression and bending.

From the above analyses, it can be concluded that the preload in the steel tubes has negligible influence on the failure modes and thermal response of the CFST columns. However, preload has significant influence on the columns' structural responses.

3.4 Fire resistance

Based on the definition of fire-resistant stated in ISO 834^[23], a column is regarded as failed if the column experiences an axial contraction of $0.01H$ mm and the rate of contraction has reached $0.003H$ mm/min, where H is the original length of the column in millimeters. Figure 10 shows the measured fire-resistance time of the 12 columns tested in the previous Sections.

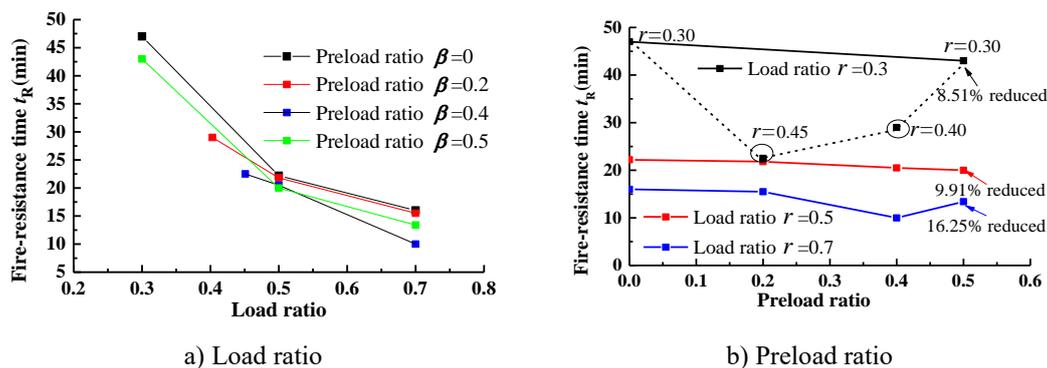


Figure 10. Loading ratios viz Fire-resistance time

The influence of preload and total axial load on the fire resistance time of the CFST columns is plotted in Figure 10. Unfortunately, the results of C12 ($r=0.3$, $\beta=0.2$) and C13 ($r=0.3$, $\beta=0.4$) are out of normal expectation due to some technical issues occurring in the tests, which will be investigated using numerical simulation in the companion paper^[23]. In fact, the load applied to C12 and C13 columns are 531kN and 595kN, rather than the respective designed values. Thus the actual load ratios of C12 and C13 are $r=0.45$ and $r=0.40$, respectively. In general, the results obtained from the tests have shown that both the load and preload ratios have significant influence on the fire resistance time. From the comparisons of the columns with different load ratios but the same preload ratio, it can be seen that the higher the load ratio is, the shorter the fire resistance time will be. From the comparisons of the columns with different preload ratios but the same total axial load ratio, it can be seen that a higher preload ratio always results in a shorter fire resistance time. This is due to the fact that the preload has an impact on the internal force carried by the concrete core and also lateral deformation of the column, which will affect its fire resistance time. The effect of preload on the fire resistance of CFST columns is more obvious when the total

axial load is higher. As shown in Figure 10b, fire resistance time is reduced by as much as 16.25% when the load ratio is 0.5, due to that the deformation caused by the preloads play a more importance role when the load ratio is higher.

4. Conclusions

Fire-resistance tests of 12 CSFT columns considering preload in the steel tube have been reported in this paper. Comparisons were made between columns with and without being preloaded, from which the influence of preload on the time-dependent temperature field, axial deformation and failure modes were studied. Finally, fire resistance times of the columns were recorded and studied. From the test results, the following observations were made.

- 1) The self-balancing device used to apply preload is effective and may be adopted by other similar tests.
- 2) For all the columns with or without being preloaded, overall buckling failure was the main failure mode, though local folding and bulging occurred to some of them. A higher load level always resulted in a greater bending deformation.
- 3) Load ratios have little influence on the temperature fields. As for structural response, a higher preload ratio always resulted in a higher axial deformation rate at the top end of the columns.
- 4) In general, a preloaded CFST column has lower fire resistance. A higher preload ratio always results in a shorter fire resistance time and this effect is more obvious when the total axial load ratio is higher.

There have been a few test cases that did not produce reliable results due to some unexpected events. This highlights the importance of numerical simulations that, after proper validation, can be used to carry out parametric studies to provide results that are more consistent. Details of numerical modelling and analyses of the tested columns and further investigations can be found in the second part of this research reported in the companion paper^[24].

Acknowledgement

The authors are grateful for the financial support from the National Natural Science Foundation of China (Grant Nos. 51508425, 51878518 and 51738011).

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