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# ISO 834 standard fire test and mechanism analysis of square tubed-reinforced-concrete columns

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## **Abstract**

The tubed-reinforced-concrete (TRC) column is an innovative steel-concrete composite column and its steel tube is terminated at beam-to-column connections to mainly work as hoop reinforcements without sustaining axial load directly. Fire performance of TRC columns differs from that of concrete-filled steel tubular (CFST) columns since the axial deformation behaviour of the TRC columns would mainly depend on the inner reinforced concrete and local buckling of steel tube is minimised. However, no research has been reported on the behaviour of square TRC columns under fire exposure. Five slender square TRC columns subjected to standard fire and axial loading were tested in this study and the effects of load ratio and load eccentricity were investigated. Failure mode of the test specimens was dominated by global flexural buckling, whereas tube local buckling was also observed. The experimental results show that load ratio has a significant influence on the fire resistance of test specimens while the influence of load eccentricity is marginal. A sequentially-coupled thermo-mechanical finite element analysis (FEA) model was developed using ABAQUS. This FEA model was validated well against the test results when using the measured column end rotations as realistic boundary conditions. Different from the case of a CFST column, the axial load applied to a TRC column in fire is mainly sustained by the concrete and reinforcing bars and the high-temperature capacity contribution of steel tube is neglectable. With the increase of exposure time, the applied load gradually transfers from concrete to reinforcements until the

31 yielding of re-bars.

32 **Keywords:** Square tubed-reinforced-concrete (TRC) column; Composite construction; Fire;  
33 Experiment; FEA modelling.

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35

## 36 **1. Introduction**

37 Tubed-reinforced-concrete (TRC) column, also known as steel tube confined reinforced  
38 concrete (STCRC) column, as shown in Fig. 1, is an innovative steel-concrete composite  
39 column, which differs from conventional concrete-filled steel tubular (CFST) column,  
40 even though their appearances are similar [1-2]. The outer steel tube in TRC columns is  
41 discontinued at the beam-to-column connections and the steel tube does not directly bear  
42 axial load and mainly works as hoop reinforcements to provide confinement to the  
43 concrete core, which means local buckling of steel tube can be effectively prevented or  
44 delayed. The steel tubes used in TRC columns are generally much thinner than those used  
45 for CFST columns; the steel tube to concrete area ratio is generally between 2%-4% for  
46 TRC columns. Unlike CFST columns, which usually do not need longitudinal re-bars if  
47 fire resistance design is not required [3], longitudinal re-bars are essential to TRC  
48 columns to resist bending moments due to the discontinuity of steel tube.

49 The concept of TRC columns was first proposed by Tommi et al. [4-6] to improve the  
50 shear capacity and ductility of reinforced concrete (RC) columns. Aboutaha and Machado  
51 [7] also considered this member as a retrofitting method to enhance the seismic  
52 performance of RC columns. In China, TRC columns are studied as a new type of  
53 composite column and their compressive behaviour and seismic performance have been  
54 investigated by many Chinese researchers, e.g. the works conducted by Han et al. [8-9],  
55 Zhang and Liu [10], Liu et al. [11], Yu et al. [12], Abdullah et al. [13], Zhou and Liu [14]  
56 and Wang et al. [15]. TRC columns were found to possess the advantages of CFST  
57 columns, i.e. high load-bearing capacity, good ductility, excellent seismic performance  
58 and ease of construction. Furthermore, the RC beam-TRC column connections could be  
59 designed and constructed following the provisions of RC structures [1-2], as shown in Fig.  
60 1, which avoids the complexity of connecting RC beams to CFST columns. In recent  
61 years, TRC columns are gaining increasing usage in high-rise buildings and large-span  
62 stadiums in China [15-16]. The details of the applications of TRC columns in typical

63 engineering projects in China are listed in Table 1. This novel type of composite column  
64 is expected to have broad application prospects worldwide.

65 Recent fire incidents such as those of the London Grenfell Tower, Dubai Torch Tower,  
66 Melbourne Lacrosse Building and Beijing CCTV Headquarters have drawn increasing  
67 attentions to the fire engineering design of high-rise buildings [17]. However, the  
68 understanding of the fire performance of TRC columns is still very limited by far. Over  
69 the past few decades, extensive studies have been conducted on the fire behaviour of  
70 CFST columns both experimentally and numerically, e.g. the works of Han [18], Lie and  
71 Kodur [19], Wang [20], Hong and Varma [21], Romero et al. [22], Tao et al. [23], Yang  
72 et al. [24], Pagoulatou et al. [25], Meng et al. [26-27], Huang and Burgess [28], Yu et al.  
73 [29] and Yang et al. [30]. Considerable research has also been carried out to investigate  
74 the fire performance of RC columns, e.g. the works of Klingsch et al. [31], Lie and  
75 Woollerton [32], Vandeveldel et al. [33], Kodur et al. [34], Tan and Yao [35], Bratina et al.  
76 [36], Wu et al. [37], Sadaoui and Khennane [38], Martins and Rodrigues [39], Bamonte  
77 and Monte [40] and Achenbach and Morgenthal [41].

78 However, when exposed to fire, TRC columns behave very differently compared to  
79 CFST columns and RC columns. Therefore, the outcomes of the research on the fire  
80 performance of CFST and RC columns are not directly applicable to TRC columns.  
81 There are two main differences between the fire behaviour of TRC columns and CFST  
82 columns:

83 (1) The axial expansion or contraction of a TRC column in fire mainly depends on the  
84 inner RC section, whereas the axial deformation of a CFST column in fire is highly  
85 affected by the steel tube. Therefore, the axial load redistributions throughout heating  
86 within the composite sections and the restraints from surrounding structures onto the  
87 heated columns are very different for these two types of columns;

88 (2) The steel tube of a CFST column sustains the axial load directly and is prone to local  
89 buckling. In fire conditions, the steel tube expands more than the concrete core and its  
90 axial stress increases significantly, leading to a much higher risk of tube local buckling.  
91 The occurrence of tube local buckling has an obvious detrimental effect on the fire  
92 resistance of CFST columns. In contrast, the steel tube in a TRC column is mainly  
93 subject to tension in the transverse direction and so tube local buckling could generally be  
94 minimised or significantly delayed.

95 Compared to RC columns, the steel tube of TRC columns can effectively prevent the  
96 concrete cover from peeling off due to fire spalling and so help maintain the integrity of

97 the concrete section and protect the re-bars against heating.  
98 To the authors' knowledge, no study has been reported on the fire behaviour of square  
99 TRC columns so far. Motivated by the increasing applications of TRC columns in  
100 engineering practices, the authors conducted a series of studies on the fire performance  
101 and post-fire behaviour of TRC columns. Experimental and numerical studies on the fire  
102 performance of circular TRC columns were conducted and reported by Liu et al. [42]. It  
103 was found that the load ratio, cross-sectional dimension and slenderness ratio are the  
104 most important factors affecting the fire resistance of circular TRC columns. A simplified  
105 design method was also proposed for the prediction of the fire resistance of circular TRC  
106 columns [42]. The aim of this research is to study and reveal the fire behaviour of square  
107 TRC columns. Fire tests were conducted on five square TRC slender columns subjected  
108 to various load ratios and load eccentricities. The temperature distribution and  
109 high-temperature deformation, failure mode and fire resistance of these square TRC  
110 columns were obtained from the tests. The influences of load ratio and load eccentricity  
111 ratio were evaluated. A sequentially-coupled thermo-mechanical FEA model was then  
112 developed and validated against the experiments. The load redistributions within the  
113 composite section during heating and loading were analysed in order to reveal the  
114 working mechanism of square TRC columns exposed to fire.

## 115 **2. Experimental investigation**

### 116 *2.1 Details of the specimens*

117 Five slender square TRC columns were tested. Three specimens were subjected to  
118 concentric load; and the other two were eccentrically-loaded. The details of these  
119 specimens are reported in Table 2, including the sectional depth  $D$ , width  $B$ , tube  
120 thickness  $t_s$  and column length  $L$ . The symbols  $\alpha$  and  $\rho$  in Table 2 represented the  
121 cross-section steel ratio (the area of steel tube over that of concrete) and reinforcement  
122 ratio (the area of steel reinforcement over that of concrete) of the column, respectively.  
123 Load ratio was found to be one of the most critical parameters that affect the fire  
124 performance of circular TRC columns [42]. Most composite columns in real engineering  
125 are under the combined effects of compression and bending, and so load eccentricity is  
126 also an important parameter. Thus, load ratio  $n$  and load eccentricity  $e$  were chosen as the  
127 key testing parameters in this paper, the values of which were used to name the  
128 specimens. For example, TRC-0.5-25 was corresponding to a specimen with a load ratio

129 = 0.5 and a load eccentricity = 25 mm. Axial load was applied onto the top of the column  
130 and maintained constant during the test. The value of the axial load  $N_f$  was obtained by  
131 the load ratio multiplying the ambient-temperature bearing capacity of the column that  
132 determined according to the Chinese design code JGJ/T471 [43]. Load ratios were 0.4,  
133 0.5 and 0.6 considering the typical load levels of steel-concrete composite columns in the  
134 fire limit state [44]. Load eccentricity ratios (defined as  $2e/D$ ) were taken as 0.2 and 0.4.  
135 As shown in Fig. 2(b), each column contained eight longitudinal reinforcements with a  
136 diameter  $\phi$  of 16 mm, as well as 8 mm diameter stirrups at 200 mm spacing. Stirrups  
137 with a diameter of 10 mm were placed at 50 mm intervals near column ends. Concrete  
138 cover, i.e. the distance from the concrete surface to the outer edge of the stirrup, was 25  
139 mm.

140 Each square steel tube was fabricated by welding two channel sections together. After  
141 placing the reinforcing cage into the steel tube centrally at the proper position, two end  
142 plates were welded to the bottom and top of the steel tube. A square hole was cut on the  
143 top end plate for concrete casting and then it was sealed. For eccentrically-loaded  
144 columns, the offset distance between the central lines of the end plates and steel tube  
145 section equalled to the load eccentricity.

146 In each fire test, an unloaded stub column of 400 mm height was placed next to the  
147 slender specimen to measure the temperature distribution across the cross-section. This  
148 measurement was believed to represent the temperature distribution within the loaded  
149 column, given that previous research conducted by Romero et al. [22] indicated that the  
150 applied load and the second-order effect barely affected the temperature distribution  
151 within a column. The uniformity of temperature distribution along the height of the  
152 furnace had already been verified in our previous testes [42]. All the cross-sectional  
153 details of these stub columns are the same as those of the slender columns. Type K  
154 (nickel-chrome) thermocouples were adopted for temperature measurements; their  
155 locations are illustrated in Fig. 2(c). The measuring points 1 and 6 were at the outer  
156 surface of the steel tube, points 2-5 were embedded in the concrete core and points 7-10  
157 were at the re-bars.

## 158 *2.2 Material properties*

159 The steel tubes and reinforcing bars were made of mild steel. The ambient-temperature  
160 mechanical properties of the steel tube and re-bars were determined by tensile coupon

161 tests according to ISO 6892-1 [45]. The test results are summarized in Table 3, including  
162 the steel tube yield strength  $f_y$ , re-bar yield strength  $f_b$ , ultimate strength  $f_u$ , elastic  
163 modulus  $E_s$ , Poisson's ratio  $\nu$  and elongation ratio  $\epsilon_f$ .  
164 Ready-mixed self-compacting concrete (SCC) was employed in the tests and the mix  
165 design is listed in Table 4. Grade 42.5 ordinary Portland cement and medium river sand  
166 with a fineness modulus of 2.5 were used and the coarse aggregate was calcareous  
167 bluestone with the grading of 5-20 mm. Mineral powder and fly ash were added as filler  
168 to improve the workability of the concrete. The measured slump flow was 700 mm.  
169 Concrete cubes of 100 mm width and 150 mm width and 150×150×300 mm prisms were  
170 cast and wrapped with tinfoil and then cured under the same condition as for the columns.  
171 The results of concrete cube compressive strength  $f_{cu}$  and elastic modulus  $E_c$  on 28 days  
172 and on the day of fire testing (190 days) are listed in Table 4. The moisture content of  
173 concrete was measured using three 100 mm cubes on the day of fire testing according to  
174 ISO 12570 [46] and the mean value was 5.4%.

### 175 *2.3 Test setup and procedure*

176 A furnace, with inner dimensions of 4200×1900×4050 mm, was used to heat the  
177 specimens. The furnace temperature-time relationship followed the ISO 834 standard fire  
178 curve. Ten gas burners were embedded at different locations of the chamber. Eight type S  
179 (platinum-rhodium) thermocouples were employed to measure the furnace air  
180 temperatures.

181 Each slender column was nominally pinned about the y-axis (shown in Fig. 2(b)) at both  
182 ends with a slenderness ratio  $\lambda$  ( $\lambda=2\sqrt{3}L/D$ ) of 52.8. This one-direction pinned boundary  
183 condition was also used in the fire tests reported in [42,47-52]. The column ends about  
184 the x-axis were fixed. The heated length of a column was 3000 mm. Right above and  
185 below the heated zone, two gaps of 30 mm width were cut as shown in Fig. 2(a). These  
186 gaps were also used to release steams due to moisture vaporization in concrete.

187 A hydraulic jack with a maximum loading capacity of 3000 kN was used to load the  
188 specimens. The slender column was erected in the test rig and then preloaded to 100 kN  
189 until all the bolts were fastened. The unloaded stub column was located next to the  
190 slender column. The slender column was loaded to the designated load  $N_f$  with an interval  
191 of 20% $N_f$  and then the axial load was kept constant by the automatic control system.  
192 Then gas burners were ignited and the column was heated under constant load until the

193 axial deformation or axial deformation rate reached the criteria described in ISO 834-1  
194 [53]. The corresponding failure time was defined as fire resistance. The test procedure of  
195 column TRC-0.4-0 is displayed in Fig. 3(a) as an example. The measured axial load-time  
196 curve of this specimen is illustrated in Fig. 3(b) and a good precision of the automatic  
197 control system was achieved.

198 To measure the lateral deformation at the mid-height of the heated part of a specimen,  
199 two wires were first fixed to the column surfaces and then connected to two vertical  
200 LVDTs out of the furnace through fixed pulleys. More details of this measurement  
201 method can be found in reference [52]. The displacement of a column during the fire test  
202 was the total displacement subtracting the displacement due to ambient-temperature  
203 loading, in order to exclude the influence of test rig deformations. Fig. 4 shows the test  
204 setup, including (1) the gas furnace, (2) the steel reaction frame, (3) the location of tested  
205 slender column, (4) the locations of furnace thermocouples, (5) the hydraulic jack, (6) the  
206 layout of axial LVDTs, (7) top boundary condition and (8) bottom boundary condition.  
207 As shown in Fig. 4(c), there were a total of eight vertical LVDTs (named by  $u_1$ - $u_8$ ) to  
208 check the deformation uniformity of the top loading device, four of which were located at  
209 the upper steel plate connected to the hydraulic jack and the other four were located at the  
210 lower steel plate with bolt holes. Two of the LVDTs  $u_4$  and  $u_7$  are not visible in Fig. 4(c);  
211 they are in the symmetrical locations to  $u_3$  and  $u_8$ . It should be noted that although the  
212 loading bearing was lubricated before each test, it was still impossible to generate an  
213 ideal pinned boundary due to the inevitable friction. The measured rotation-time  
214 relationships of the top end plate could be used to reflect the real boundary condition and  
215 this will be discussed hereinafter.

## 216 **3 Test results and discussions**

### 217 *3.1 Failure modes*

218 The failure criterion of axial displacement rate in ISO 834-1 [53] was reached with a  
219 value of  $0.003L$  mm/min (11.43 mm/min in this paper). Then the columns were unloaded  
220 and all the burners were turned off. Most of the columns experienced global buckling  
221 failure except the column TRC-0.6-0 that failed by concrete crushing and buckling of  
222 re-bars in compression. This compression failure was also observed in previous research  
223 on CFST columns conducted by Lie and Chabot [54-55], Kodur and Latour [56], Wang

224 and Young [57] and Xiong and Liew [58]. The typical failure modes of the columns after  
225 unloading are presented in Fig. 5. The midspans of the columns exhibited obvious lateral  
226 deformations and the column-end rotations were considerable. Though designed not to  
227 carry any axial loads directly, the steel tube of the square TRC column experienced local  
228 buckling especially in the column mid-height, which is in accordance with the findings in  
229 the fire tests of circular TRC columns [42] and the post-fire tests of circular and square  
230 TRC columns [59-62]. The occurrence of tube local buckling may be due to the axial  
231 stress in the steel tube caused by the inevitable bond and friction at the steel-concrete  
232 interface. Generally, this axial stress accumulates from the column end to the mid-height  
233 [63].

234 Post-fire deformations of the specimens including the residual column lengths  $L_{res}$ ,  
235 residual end plate rotations  $\varphi_{res,top}$  and  $\varphi_{res,bot}$ , maximum residual lateral deformations  $w_{max}$   
236 and the corresponding location heights  $x_{max}$  are displayed in Fig. 5 except for TRC-0.6-0.  
237 These residual deformations were smaller than the real deformations of the columns at  
238 the end of the fire tests due to the deformation-recovery caused by cooling and unloading.  
239 Fig. 5(f) shows the two cutting gaps of specimen TRC-0.4-0 after fire test. The concrete  
240 cover within these gaps was crushed due to the lack of steel tube confinement. Although  
241 these gaps narrowed due to the compression deformation of the confined RC section and  
242 the thermal expansion of the steel tube, the gaps were not eliminated.

243 After the fire tests, the outer steel tubes were removed to examine the inner concrete  
244 cores and re-bars. For the specimen TRC-0.5-25, the concrete in the compression zone at  
245 mid-height was crushed together with the buckling of the reinforcements at the same  
246 location and apparent transverse cracking was observed in the corresponding tension  
247 zone, as shown in Figs. 6(a)-6(c). It can be seen from Figs. 6(d)-6(f) that the column  
248 TRC-0.6-0 failed by local concrete crushing and all the longitudinal reinforcements  
249 buckled by compression at the same location.

### 250 *3.2 Temperature histories*

251 The measured temperature curves of the furnace thermocouples (T1-T8) during the fire  
252 test of TRC-0.4-0 was compared with the standard ISO 834 curve in Fig. 3(c). The spatial  
253 distribution of the furnace temperature was uniform and the use of unloaded stub  
254 columns to measure the temperature distribution within the slender columns was feasible.  
255 The average furnace air temperature-time curves of all the tests are summarized in Fig.

256 7(a), which shows a good precision of furnace air temperature control.  
257 As shown in Figs. 7(b)-7(h), a good uniformity of the temperature fields within these  
258 specimens was substantiated. The differences between these curves in Fig. 7(b) may be  
259 attributed to that the fire insulation measures to some of the steel tube thermocouples  
260 were not tight enough and these thermocouple results were affected by the flames.  
261 Though tips of thermocouples 1 and 6 had been wrapped locally with insulation material.  
262 Symmetric measuring points of re-bars generally presented close temperature  
263 measurements, which revealed the uniformity of heating between different faces of a  
264 column. Re-bars at the cross-section corners (Points 8 and 9 in Fig. 2(c)) were hotter than  
265 those at the edge midpoints (Points 7 and 10 in Fig. 2(c)), which was caused by different  
266 dimensionalities of heat transfer. Visible temperature plateau in concrete occurred at  
267 around 100-150 °C due to the water evaporation and migration.

### 268 3.3 Deformation behaviour

269 The mean axial displacement of specimen TRC-0.4-0, measured from eight vertical  
270 LVDTs  $u_1$ - $u_8$  in Fig. 4(c), is shown in Fig. 3(d). The graph legends of Fig. 3(d) indicate  
271 which LVDTs are considered to obtain the mean displacement values; for example,  
272  $Ave(u_1, u_2)$  is the average of the LVDTs  $u_1$  and  $u_2$ . The overlapping of curves  $Ave(u_1, u_2)$   
273 and  $Ave(u_3, u_4)$  indicates the upper loading plate moved vertically and maintained  
274 horizontal without rotation. There were obvious differential displacements between  
275  $Ave(u_5, u_6)$  and  $Ave(u_7, u_8)$ , due to the lower steel plate rotation  $\varphi(t)$ , which was taken as  
276 the difference between  $Ave(u_5, u_6)$  and  $Ave(u_7, u_8)$ , divided by the distance between  
277 LVDTs  $u_5$  and  $u_7$ .  $Ave(u_1, u_2, u_3, u_4)$  and  $Ave(u_5, u_6, u_7, u_8)$  were similar, indicating that the  
278 deformation of the test rig between the lower and upper steel plates had little influence on  
279 the measured specimen axial displacement. The axial displacement of each column was  
280 finally taken as  $Ave(u_5, u_6, u_7, u_8)$ .

281 The deformation-time relationships of the specimens are summarized in Fig. 8, including  
282 the axial deformation  $u(t)$  and lateral deformation  $w(t)$ . Positive vertical deformations  
283 correspond to axial elongation and negative ones were for the column shortening. The  
284 influence of the thermal expansions of the two wires used to measure the specimen lateral  
285 deformation was removed by averaging the measured deformation of these two wires, as  
286 described in reference [52]. The lateral deformation of TRC-0.4-0 was not recorded to  
287 failure because the wires broke prematurely. All columns failed by exceeding the limit of

288 the axial deformation rate. The fire resistance  $t_{FR}$  of the specimens were marked using red  
289 dots in Fig. 8 and the results of  $t_{FR}$  for these five specimens are included in Table 2. The  
290 temperature reached by the steel tube at failure time was defined as limiting temperature.  
291 Although the limiting temperature of steel tube alone should not be able to define the fire  
292 resistance of TRC columns, it can reflect the influence of fire on the TRC columns to  
293 some extent.

### 294 *3.4 Discussions of results*

295 The fire behaviour of square TRC columns is the combined effects of two phenomena, (1)  
296 axial elongation due to thermal expansion and (2) axial shortening caused by  
297 temperature-induced material degradation under loading. Depending on which  
298 phenomenon dominates, the evolution of the column axial displacement with time can be  
299 divided into several phases. As shown in Fig. 8, the axial deformation of specimens  
300 TRC-0.4-0, TRC-0.5-0 and TRC-0.5-25 experienced three phases: Phase 1 - elongation,  
301 Phase 2 - shortening and Phase 3 - failure. During Phase 1, the heating rate was high and  
302 the effect of thermal expansion was dominant. The durations of axial elongation for these  
303 three columns were 50.5 min, 2.2 min and 40.7 min, respectively and the corresponding  
304 maximum expansion values were 0.47 mm, 0.09 mm and 0.39 mm. With further heating,  
305 the material properties degraded notably as the specimen temperature increased, causing  
306 axial contraction under loading which dominated over the thermal expansion. This phase  
307 is defined as Phase 2. In Phase 3, as the materials degraded further with the temperature  
308 rising, when the resistance of the column fell below the applied load, failure occurred and  
309 an abrupt increase of the axial deformation was recorded. Due to the large load ratio,  
310 specimen TRC-0.6-0 only underwent crushing failure in compression. For column  
311 TRC-0.5-50, the axial deformation experienced four phases, which started from  
312 shortening, switched to elongation and then returned to shortening before failure. The  
313 first contraction phase last about 9 min and the maximum compressive deformation was  
314 only 0.2 mm. Apart from the possible influence of measurement errors, the occurrence of  
315 this phase may be attributed to the second-order effect caused by large eccentricity.

#### 316 *3.4.1 Effect of load ratio*

317 The influence of load ratio on the axial deformation, lateral deformation, endplate  
318 rotation, steel tube limiting temperature and fire resistance of the tested square TRC

319 columns are plotted in Figs. 9(a)-9(d). The column with larger load ratio experienced  
320 larger axial compression deformation, mid-span lateral deformation and endplate rotation  
321 at the same fire exposure time. Fig. 9(b) shows that the lateral displacement of specimen  
322 TRC-0.6-0 is considerate and of the same order as for the other specimens, whereas Fig.  
323 5(c) shows that this specimen being quite straight after testing. The reason might be that  
324 most of the global lateral deformation of this column recovered after cooling and  
325 unloading.

326 The fire resistance of concentrically-loaded columns decreases from 86.7 min to 38.1 min,  
327 as load ratio increases from 0.4 to 0.5. The fire resistance of the specimen TRC-0.6-0 is  
328 only 13.5 min. The obtained steel tube limiting temperatures of these three TRC columns  
329 subject to load ratios 0.4, 0.5 and 0.6 are 917.6 °C, 760.5 °C and 454.9 °C, respectively. It  
330 is interesting to find in Fig. 9(d) that the increase of fire resistance is not proportional to  
331 the load ratio decrease. For instance, comparing specimens TRC-0.6-0 and TRC-0.5-0,  
332 the fire resistance increases by 181.7% when the load ratio decreases by 16.7%. When  
333 the load ratio decreases from 0.5 to 0.4 (20%), the improved level of fire resistance is  
334 127.5%. Compared to the apparent increasing levels of fire resistance (181.7% and  
335 127.5%), the corresponding increase levels in the limiting temperatures of steel tube are  
336 only 67.2% and 20.7%. This is due to the continuously decreasing heating rate of the ISO  
337 834 standard fire, i.e. the rate at 13.5 min is 11 °C/min and decreases to only 1.7 °C/min  
338 at 86.7 min.

### 339 *3.4.2 Effect of load eccentricity*

340 As presented in Figs. 9(e)-9(h), the overall lateral deformation of the column and the  
341 endplate rotation generally increase with the increasing of load eccentricity. At the same  
342 heating time, the columns under eccentric load generally experienced smaller axial  
343 compressive deformation than the concentrically-loaded specimen. In terms of fire  
344 resistance, TRC-0.5-25 with a medium eccentricity of 25 mm obtained the longest fire  
345 resistance 45.5 min compared to specimens TRC-0.5-0 (38.1 min) and TRC-0.5-50 (35.6  
346 min). The corresponding limiting temperatures of steel tube are 760.5 °C, 772.5 °C and  
347 694.3 °C, respectively.

348 Within the research scope of this paper, the influence of load eccentricity on the fire  
349 resistance of the specimens subject to the same load ratio 0.5 is found to be modest. On  
350 one hand, the existence of load eccentricity increases the second-order effect and

351 decreases the high-temperature load-bearing capacity of the column, which might lead to  
352 the decrease of fire resistance. On the other hand, under the same load ratio, the applied  
353 load on an eccentrically-loaded column is lower than that on a concentrically-loaded  
354 column, which would be beneficial for the fire resistance of the former. Compared with  
355 the concentrically-loaded specimen TRC-0.5-0, the fire resistance increases by 19.2%  
356 and -6.9% respectively for columns with load eccentricity ratios of 0.2 and 0.4, as the  
357 applied loads decrease by 31.4% and 47.5%. This indicates that the load eccentricity ratio  
358 of 0.2 has a positive effect on fire resistance whereas a larger load eccentricity ratio 0.4  
359 results in a lower fire resistance.

## 360 **4. Numerical simulations**

361 A sequentially-coupled thermal-stress analysis model was built using the program  
362 ABAQUS [64]. The mesh sizes adopted for the heat transfer and stress analyses were the  
363 same. The measured specimen dimensions, material properties, applied loads and furnace  
364 temperature-time relationships were adopted in the FEA modelling. Considering the  
365 symmetries in the experiments, only half of the composite cross-section was built.

### 366 *4.1 Thermal analysis*

367 For the heated faces of the column, a convective coefficient of  $25 \text{ W}/(\text{m}^2 \cdot \text{K})$  was adopted  
368 and a comprehensive emissivity coefficient of 0.5 that recommended by ECCS 1988 [65]  
369 was used. This emissivity value was found to give accurate predictions for fire  
370 experiments of composite columns [42,52,59-62,66-71]. For the part of the specimen  
371 which was out of the furnace, there was conduction from the heated part of the specimen,  
372 followed by radiation and convection to the environment. This was considered by  
373 adopting a convective coefficient of  $9 \text{ W}/(\text{m}^2 \cdot \text{K})$ , which also included the effects of  
374 radiation, as given in EC1 [72]. For the parts of the specimen that were in the furnace but  
375 thermally insulated, it was assumed that there was only conduction from the heated part.  
376 The thermal models of concrete and steel that recommended by ASCE [73] and EC2 [74]  
377 have been successfully used for simulations of CFST columns by many researchers and  
378 these two models are expected to yield good predictions in the thermal simulation of TRC  
379 columns. The ASCE model is the same as that proposed by Lie [75] and it has been used  
380 to predict the thermal response of circular TRC columns [42]. Therefore, the ASCE  
381 model was still used in the paper. The measured moisture content was considered in the

382 calculation of the specific heat of concrete to reflect the influence of water evaporation. A  
383 thermal resistance of  $0.01(\text{m}^2\cdot\text{K})/\text{W}$  was considered at the steel-concrete interface, as  
384 recommended by Ding and Wang [66] and Lv et al. [76]. The nodes of the re-bars were  
385 tied to those of concrete at the same locations. The element types were DC3D8, DS4 and  
386 DC1D2 for concrete, steel and reinforcements, respectively.

387 As shown in Fig. 10, the thermal analysis model was validated against the measured  
388 temperatures of the tested specimens. The FEA results matched very well with the  
389 experimental data, especially for the temperatures of the steel tube and re-bars. The  
390 discrepancy between the predicted and measured concrete temperatures may be caused  
391 by: 1) the thermocouples may be slightly misplaced; 2) the ASCE thermal models of  
392 concrete may be different from those of the SCC used in the test; and 3) the moisture  
393 movement inside concrete was not considered in the model.

394 The heat transfer analysis was further validated against experiments of circular TRC  
395 columns conducted by Liu et al. [42]. These experiments are the most relevant to this  
396 study. The modelling and test results agreed well with each other, as shown in Figs.  
397 11(a)-11(b).

## 398 *4.2 Mechanical analysis*

399 In the mechanical analysis, the concrete damage plasticity (CDP) model was employed  
400 for concrete. In the CDP model, the dilation angle is  $36^\circ$  and the default values for the  
401 flow potential eccentricity, the ratio of the second stress invariant on the tensile meridian  
402 and the viscosity parameter, given in the ABAQUS manual, were adopted. As for the  
403 ratio of initial equibiaxial compressive yield stress to initial uniaxial compressive yield  
404 stress, the temperature-dependent formula proposed by Gernay et al. [77] was used. The  
405 temperature-dependent constitutive model for concrete in compression given by Lie [72],  
406 which is the basis of the ASCE [73] model, was used in this paper. This model is  
407 presented as the  $\sigma_{cc,T}-\varepsilon_{cc,T}$  relationship in Eq. (1). As for the high-temperature tensile  
408 constitutive model of concrete, the stress-strain relationship  $\sigma_{ct,T}-\varepsilon_{ct,T}$  recommend by  
409 Hong and Varma [21] was adopted, which is shown in Eq. (2). The high-temperature  
410 stress-strain relationship for hot rolled reinforcing steel given in EC2 [74] and that for  
411 carbon steel given in EC3 [78] were employed in this study. The EC2 and EC3 equations  
412 (Eq. (3)) are identical. The only difference between the two is in the values of the  
413 high-temperature reduction factors, i.e. the slope of the linear elastic range  $E_{sT}$ , the

414 proportional limit  $f_{pT}$  and the effective yield strength  $f_{yT}$ . It should be noted that the  
 415 transient strain and creep of concrete and the creep of steel were implicitly included in  
 416 these material models.

$$\sigma_{cc,T} = \begin{cases} f'_{cT} \left[ 1 - \left( \frac{\varepsilon_{\max} - \varepsilon_{cc,T}}{\varepsilon_{\max}} \right)^2 \right] & \varepsilon_{cc,T} \leq \varepsilon_{\max} \\ f'_{cT} \left[ 1 - \left( \frac{\varepsilon_{cc,T} - \varepsilon_{\max}}{3\varepsilon_{\max}} \right)^2 \right] & \varepsilon_{cc,T} > \varepsilon_{\max} \end{cases} \quad (1)$$

417 where  $f'_{cT} = \begin{cases} f'_c & 0^\circ\text{C} < T < 450^\circ\text{C} \\ f'_c \left[ 2.011 - 2.353 \left( \frac{T-20}{1000} \right) \right] & 450^\circ\text{C} \leq T \leq 874^\circ\text{C}, f'_c \text{ is the cylinder compressive} \\ 0 & T > 874^\circ\text{C} \end{cases}$

418 strength of concrete at room temperature,  $\varepsilon_{\max} = 0.0025 + (6T + 0.04T^2) \times 10^{-6}$ .

$$\sigma_{ct,T} = \begin{cases} E_{cT} \varepsilon_{ct,T} & \varepsilon_{ct,T} \leq \varepsilon_{cr} \\ f'_{tT} - 0.1f'_{tT} \frac{\varepsilon_{ct,T} - \varepsilon_{cr}}{\varepsilon_{cr}} & \varepsilon_{cr} < \varepsilon_{ct,T} \leq 2\varepsilon_{cr} \\ 0.9f'_{tT} & \varepsilon_{ct,T} > 2\varepsilon_{cr} \end{cases} \quad (2)$$

419 where  $f'_{tT} = 0.09f'_{cT}$ ,  $\varepsilon_{cr} = f'_{tT} / E_{cT}$ .

$$\sigma_{sT} = \begin{cases} E_{sT} \varepsilon_{sT} & \varepsilon_{sT} \leq \varepsilon_{pT} \\ f_{pT} - c + \frac{b}{a} \sqrt{a^2 - (\varepsilon_{yT} - \varepsilon_{sT})^2} & \varepsilon_{pT} < \varepsilon_{sT} \leq \varepsilon_{yT} \\ f_{yT} & \varepsilon_{yT} < \varepsilon_{sT} \leq \varepsilon_{tT} \\ f_{yT} \frac{1 - (\varepsilon_{sT} - \varepsilon_{tT})}{\varepsilon_{uT} - \varepsilon_{tT}} & \varepsilon_{tT} < \varepsilon_{sT} < \varepsilon_{uT} \\ 0 & \varepsilon_{sT} = \varepsilon_{uT} \end{cases} \quad (3)$$

420 where  $\varepsilon_{pT} = f_{pT} / E_{sT}$ ,  $\varepsilon_{yT} = 0.02$ ,  $\varepsilon_{tT} = 0.15$ ,  $\varepsilon_{uT} = 0.2$ ,  $a^2 = (\varepsilon_{yT} - \varepsilon_{pT})(\varepsilon_{yT} - \varepsilon_{pT} + c / E_{sT})$ ,

421  $b^2 = c(\varepsilon_{yT} - \varepsilon_{pT})E_{sT} + c^2$ ,  $c = \frac{(f_{yT} - f_{pT})^2}{(\varepsilon_{yT} - \varepsilon_{pT})E_{sT} - 2(f_{yT} - f_{pT})}$ .

422 The temperature-dependent equation for the concrete Poisson's ratio proposed by Gernay  
 423 et al. [77] was adopted in the analysis. The thermal expansion coefficient of concrete was  
 424 assumed to be constant, which is  $6 \times 10^{-6}/^\circ\text{C}$ , as adopted by Hong and Varma [21], Liu et  
 425 al. [42] and Espinos et al. [79]. The temperature-dependent thermal expansion  
 426 coefficients recommended in EC3 [78] were used for the steel tube and reinforcement bar.  
 427 General surface-to-surface contact, with a friction coefficient of 0.3, was used for the  
 428 steel-concrete interface. The re-bars were embedded into the concrete to achieve the

429 deformation compatibility. An initial imperfection with the value of 1/1000 of the column  
430 length was included and the corresponding shape was the first buckling mode. Element  
431 types C3D8R, S4R and T3D2 were used to model concrete, steel tube and re-bar,  
432 respectively. In the FEA, the failure of the column was defined based on the same failure  
433 criteria as for the testing.

434 As discussed in Section 2.3, an ideal pinned boundary condition is difficult to realize and  
435 the actual boundary condition of the testing should involve a certain degree of rotational  
436 restraint. To evaluate the impact of the column-end rotational restraint, three different  
437 boundary conditions, i.e. pinned, fixed and the measured experimental rotation-time  
438 relationship  $\varphi(t)$  were adopted in the FEA. The modelling results are shown in Figs.  
439 12(a)-12(e). In the pinned boundary condition, the column top is only free to rotate in one  
440 direction (i.e. rotate about the y-axis in Fig. 2(b)) and move along the axial direction; the  
441 column bottom is assumed to rotate only about the y-axis of the column cross-section. As  
442 for the fixed boundary condition, the column top is only free to move along the  
443 longitudinal axis; all the other degrees of freedom of the column bottom end are restricted.  
444 When the measured column end rotation-time relationship is adopted as the boundary  
445 condition, the column top could only move along the axial direction and rotate about the  
446 cross-section's y-axis; the column bottom is only able to rotate about the y-axis. The  
447 measured  $\varphi(t)$  curve in Fig. 9(c) or Fig. 9(g) is set as the amplitude of the column rotation  
448 in ABAQUS. The rotation of the column bottom end was not measured during the fire  
449 test and it was assumed to be the same as the measured rotation of the column top end,  
450 since the measured post-fire column-end rotations at the top and bottom were almost  
451 identical, as shown in Fig. 5. It can be found from Fig. 12 that the test fire resistance lies  
452 between the FEA results of pinned and fixed boundary conditions. The actual  $\varphi(t)$   
453 relationship can be used as the real boundary condition and a similar simulation approach  
454 was also employed by Neuenschwander et al. [80]. The lateral-displacement-time  
455 relationships given by FEA were also compared with the test results in Figs. 12(f)-12(j)  
456 and a pretty good agreement was achieved. As a typical example, the failure mode of  
457 specimen TRC-0.5-50 given by the FEA modelling is illustrated in Fig. 5(e), together  
458 with the test pictures. The nonlinear FEA model can capture both the global buckling of  
459 the whole specimen and the local buckling of the steel tube.

460 The mechanical FEA model was further validated against the measured axial  
461 displacement-time curves of circular TRC columns [42], as illustrated in Figs.

462 11(c)-11(d). Moreover, the fire resistance of a total of 84 composite columns, including  
463 five square TRC columns tested in this research, four circular TRC columns in [42], 21  
464 square CFST columns from the experiments conducted by Han et al. [47], Espinos et al.  
465 [48] and Lie and Chabot [54-55] and 54 circular CFST columns reported by Espinos et al.  
466 [48], Moliner et al. [50], Lie and Chabot [54-55] and Han et al. [81] were modelled and  
467 the results are in Fig. 11(e). The details of these fire tests on TRC and CFST columns and  
468 the comparison of the fire resistance between the FEA predictions and the test results are  
469 summarized in Table 5. The mean value of the ratio between the modelled fire resistance  
470  $t_{FR,FE}$  and measured one  $t_{FR,test}$  is 1.05 and the standard deviation is 0.18, indicating a good  
471 agreement considering the complexity and results variability of fire tests.

### 472 *4.3 Load redistribution analysis*

473 During the fire exposure, the non-uniform temperature distribution within the column  
474 cross-section causes different thermal expansions and material degradations. As a result,  
475 the axial load resisted by the column will be redistributed within the composite section.  
476 The load redistribution within the mid-span cross-section of square TRC columns in fire  
477 is analysed using the FEA model in Section 4.2. Axial force ratio is defined as the axial  
478 force of concrete, steel tube or re-bars over that of the whole cross-section. Fig. 13(a)  
479 shows the axial force ratio-time curves for concrete core, reinforcement and steel tube of  
480 specimen TRC-0.5-0. The axial force in the steel tube is small though there are bond  
481 stress and friction between the steel tube and concrete core. The axial force ratio of the  
482 concrete core decreases from 82.3% to 64.5% and then keeps almost constant.  
483 Simultaneously, the axial force born by the reinforcements firstly increases and then  
484 remains almost unchanged. This load redistribution may be caused by the fact that  
485 heating causes the decrease of the stiffness of the outer concrete layers and thus increases  
486 the strain of concrete, resulting in the increase of the longitudinal strains of the re-bars as  
487 plane cross-sections remain plane. Fig. 13(b) shows the development of normalized stress  
488 over time during heating for reinforcement bars at different locations.  $S_b$  is the  
489 longitudinal stress of re-bar (the positive value of  $S_b$  corresponds to tensile stress).  $f_{bT}$  is  
490 the high-temperature yield strength of the reinforcement and it is equal to the  
491 ambient-temperature strength, since all the reinforcement temperatures do not exceed 300  
492 °C throughout this test. All the longitudinal stresses in the re-bars increase almost linearly  
493 in the first 20 min of heating until yielding occurs. After that, the stresses of the re-bars in

494 the tension zone of the cross-section decrease slightly, which is caused by the increasing  
495 second-order effect.

496 The axial stresses of six concrete nodes at different fire exposure moments are plotted in  
497 Fig. 13(c), in which positive value represents tensile stress. The whole concrete section is  
498 under compression after the ambient-temperature loading and the axial stress along the  
499 x-axis distributes linearly since the section remains plane. During the heating process, the  
500 stress evolution of a certain node is affected by the high-temperature material degradation  
501 as well as the differential thermal stresses that caused by the non-uniform temperature  
502 distribution of the concrete section. The outer concrete layers near the steel surface are  
503 under thermal compressive stresses while the inner layers are under tension. The stress of  
504 node 1 is always the highest during the heating followed by that of node 6. The increase  
505 of the compressive stress of node 6 until 10 min heating is mainly caused by the increase  
506 of thermal compressive stress and the continual stress decrease in the later stage of  
507 exposure is due to the increasing second-order effect and the material degradation. The  
508 compressive stresses of inner nodes 3 and 4 keep decreasing until 30 min exposure,  
509 which is a result of the increasing thermal tensile stress. After that, here occur  
510 compressive stress increases in these two nodes since the elastic modulus of the outer  
511 concrete layers decrease significantly and the axial load is gradually transformed to the  
512 inner layers.

513 As presented in Fig. 14(a), the evolutions of the load redistributions of specimens  
514 TRC-0.4-0, TRC-0.5-0 and TRC-0.6-0 follow similar patterns. The axial load is  
515 continuously redistributed from concrete to re-bars until the reinforcements yield. Before  
516 reinforcement yielding, a higher load ratio leads to a higher percentage of axial force in  
517 the re-bars, indicating a higher contribution of re-bars to the total load-bearing capacity.  
518 However, the reinforcements also yield earlier in columns subject to higher load ratio and  
519 the load redistribution stops when yielding occurs. The load redistribution in specimen  
520 TRC-0.4-0 lasts for the longest time, and so the final axial force ratio of re-bars is also  
521 the highest. For specimen TRC-0.4-0, the force in concrete recovers slightly towards the  
522 end of heating. This may be due to the strength loss of the re-bars after long heating and  
523 so part of the load is transferred back to the concrete core. For the columns TRC-0.5-0,  
524 TRC-0.5-25 and TRC-0.5-50, the axial force ratio-time curves are almost the same in the  
525 early stage of fire exposure, as shown in Fig. 14(b). It is obvious that and the axial load in  
526 the eccentrically-loaded columns is transferred back to concrete in the latter stage of  
527 heating. This phenomenon is attributed to the influence of the bending moment caused by

528 load eccentricity and increasing second-order effect. The re-bars in the compression zone  
529 yield while the ones in the tension zone undergo obvious stress drops.

530 The fire behaviour of a CFST column was compared with that of a TRC column to  
531 illustrate the difference of fire performance between these two composite members. The  
532 infill of the CFST column was bar-reinforced concrete since the load distribution within  
533 this kind of CFST column could also occur among the steel tube, concrete core and  
534 re-bars, which is comparable with the case of the TRC column. The load ratio of the TRC  
535 column was 0.5 and the CFST column had the same applied load as the TRC column.  
536 Compared to the TRC column, the steel ratio of the CFST column was increased from  
537 3.62% to 8.0%, a value within the common range 4%-20% for CFST columns. Other  
538 details of these two columns were all the same as those of the test TRC specimens in  
539 Section 2. Simply-pinned boundary conditions were employed in the simulation. The  
540 results of the axial deformation-time curves and the sectional load redistributions in the  
541 heating procedure are displayed in Figs. 15(a)-15(b). The CFST column had a higher fire  
542 resistance than the TRC column, which may be explained by the lower load ratio for the  
543 CFST column. Different from the axial deformation behaviour of the square TRC  
544 columns that discussed in Section 3.4, the axial deformation curve of the CFST column  
545 generally consists of four stages and there was a separation in the axial direction between  
546 the steel tube and the RC section in the first 3 min of the heating. This was consistent  
547 with the findings reported by Espinos et al. [79]. The axial load redistribution in a TRC  
548 column generally occurred only within the concrete and the re-bars. However, the axial  
549 load applied to a CFST column was first transferred to the steel tube and then gradually  
550 transferred back to the inside RC section, as shown in Fig. 15(b). For both of these two  
551 columns, the axial load was mainly sustained by the RC section at the failure stage.

552 To clarify the fire performance difference between TRC columns and CFST columns  
553 further, two columns of 400 mm width were analysed and the results are shown in Figs.  
554 15(c)-15(f). These two columns were subject to the same axial load, 0.5 times of the  
555 ambient-temperature bearing capacity of the TRC column. The steel ratios of the TRC  
556 column and CFST column were 3% and 8%, respectively. As shown in Figs. 15(e)-15(f),  
557 both the TRC column and CFST column failed mainly by global buckling. The steel tube  
558 local buckling of the TRC column was slight and mainly occurred at the concave side of  
559 the column mid-height. For the CFST column, considerable tube local buckling occurred  
560 at the mid-height and two ends of the column on all four sides. This may be because that  
561 the steel tube in this CFST column sustained up to 86% of the axial load in its expanding

562 stage. Contrary to the comparison result in Fig. 15(a), fire resistance of the CFST column  
563 was shorter than that of the TRC column, which may be caused by the negative influence  
564 of severe tube local buckling.

## 565 **5. Conclusions**

566 Five slender square tubed-reinforced-concrete columns were tested under combined  
567 thermal and mechanical actions. A FEA model was developed and validated against  
568 experimental results. Based on the experimental and numerical work conducted, the  
569 following conclusions can be drawn.

570 1) The main failure mode of the tested square TRC columns in fire is global buckling,  
571 together with slight local buckling of the steel tube. At the mid-height of the columns,  
572 concrete is crushed and steel reinforcements buckle in the compression zone; and  
573 transverse cracks of concrete are observed in the corresponding tension zone.

574 2) The development of the axial deformation of the tested square TRC columns generally  
575 consists of three phases, elongation, shortening and failure. Runaway failure is observed  
576 in most specimens. Fire resistance of the tested square TRC columns decreases  
577 significantly with the increase of load ratio from 0.4 to 0.6 and the effect of load  
578 eccentricity on fire resistance is unobvious.

579 3) The column end rotations measured during the experiments can be used to represent  
580 the realistic boundary conditions of the test specimens. The use of the measured column  
581 end rotations, instead of ideal pinned or fixed condition, as the boundary conditions of the  
582 numerical model considerably improves the agreement between the modelling and test  
583 results.

584 4) Through the load redistribution analysis on the FEA model, it is found that the axial  
585 load is gradually transferred from the concrete core to the steel reinforcements during  
586 heating. Before the steel reinforcements yield, a higher percentage of load is redistributed  
587 to the reinforcements as load ratio increases, whereas the case is opposite after  
588 reinforcements yielding. Load eccentricity does not affect the load redistribution in the  
589 early stage of heating, but the load will be transferred back to concrete in the later stage  
590 of heating for specimens under eccentric load.

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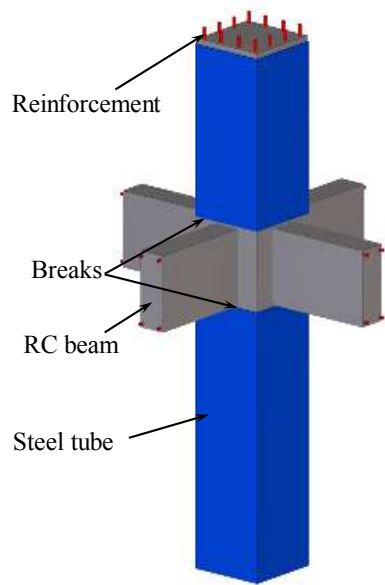
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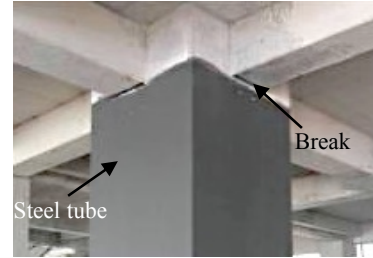
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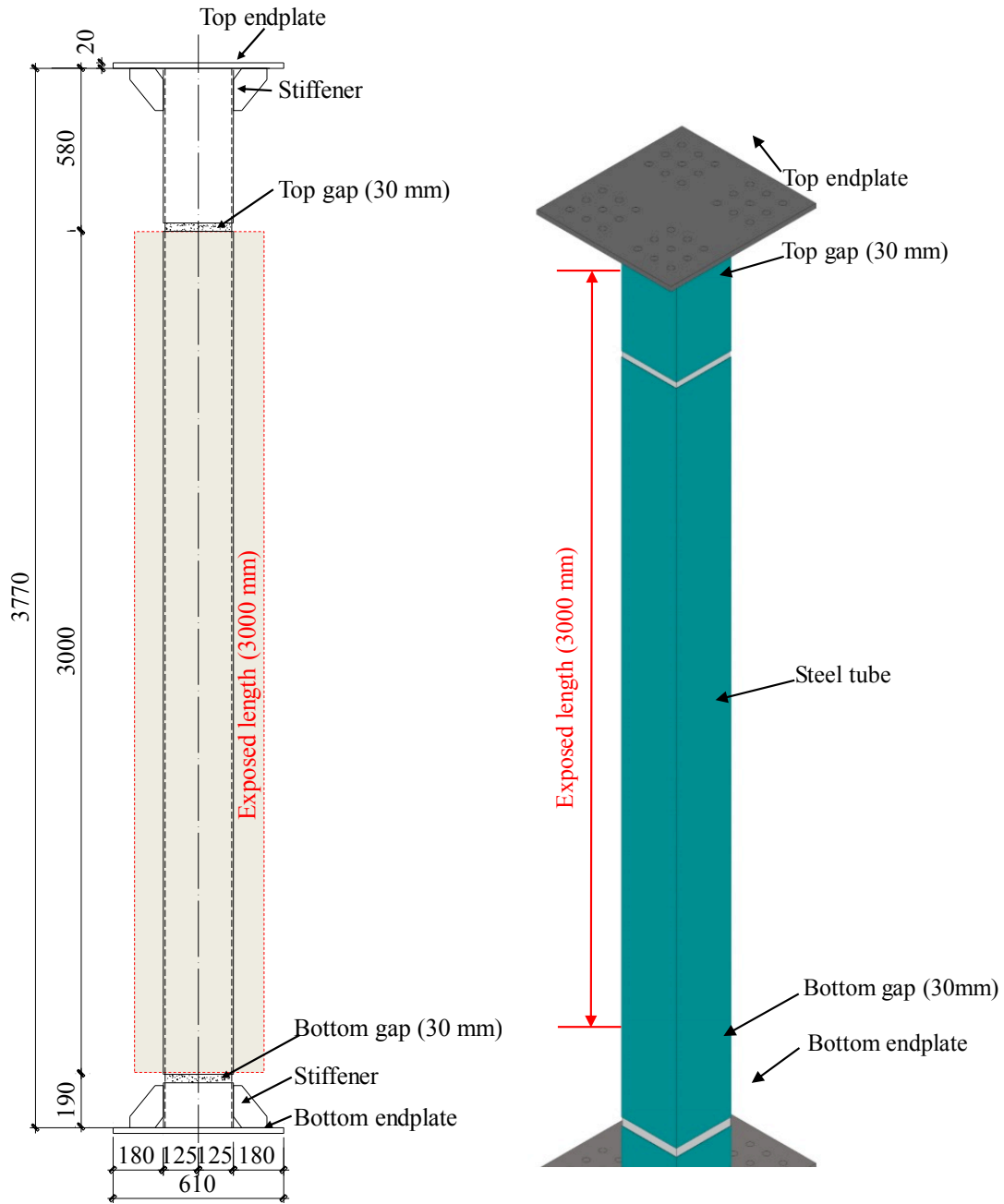


(a) TRC column

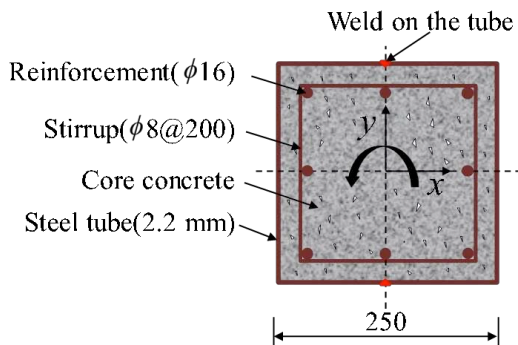


(b) TRC column-RC beam connection

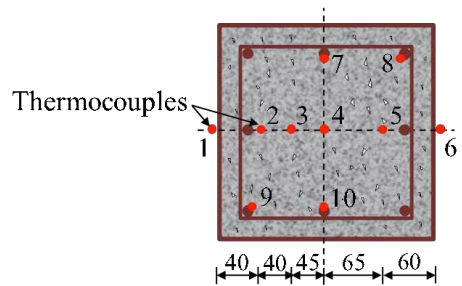
Fig. 1. Schematics of TRC column and TRC column-RC beam connection



(a) 2D and 3D schematic diagrams

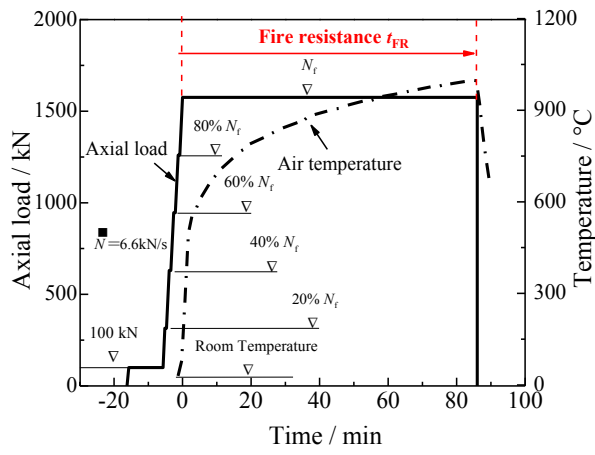


(b) Cross-section details

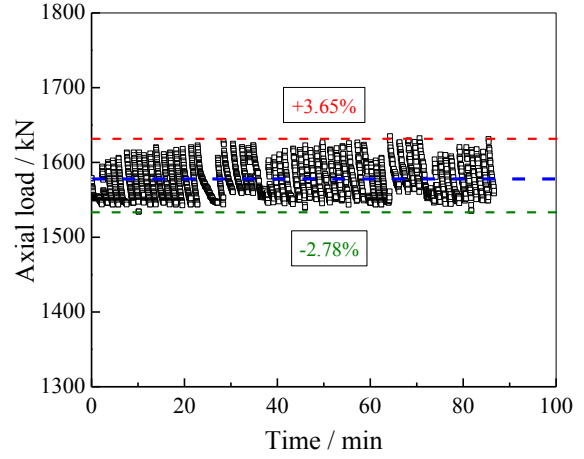


(c) Arrangement of thermocouples

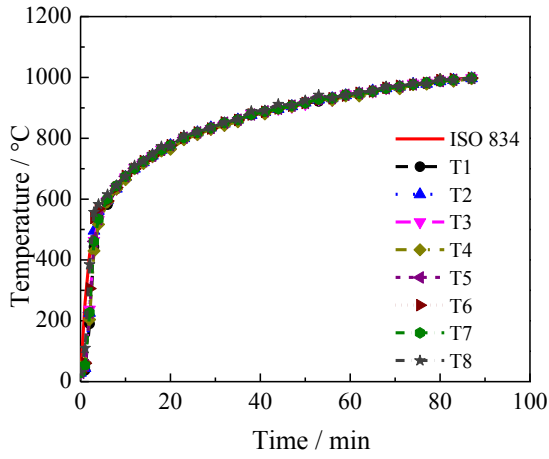
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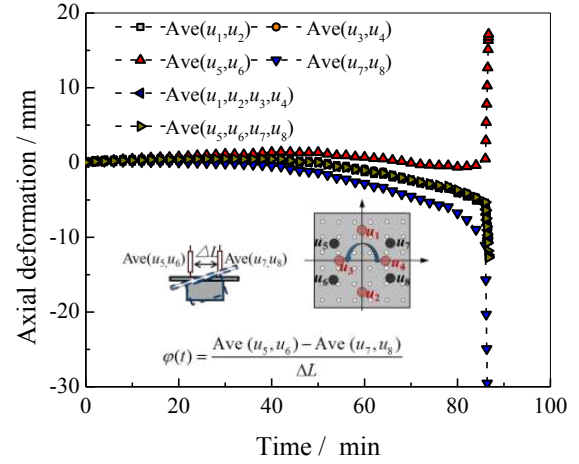
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(b) Loading precision



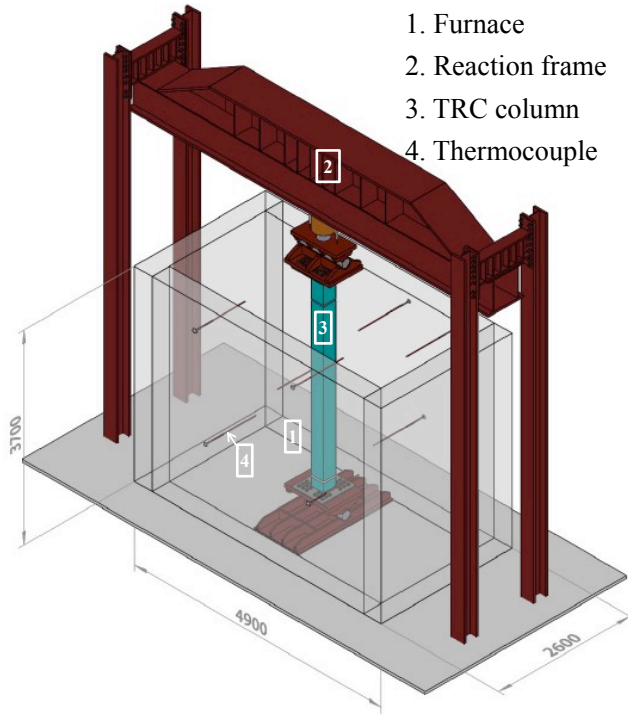
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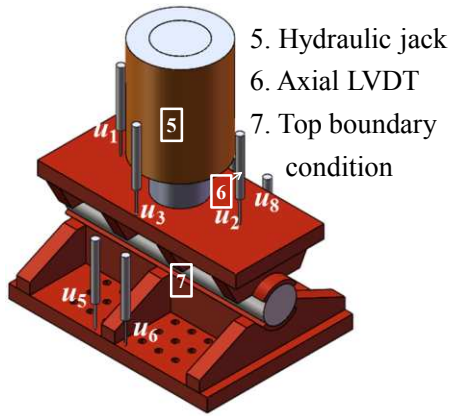
TRC-0.4-0



(a) Sketch of the test setup



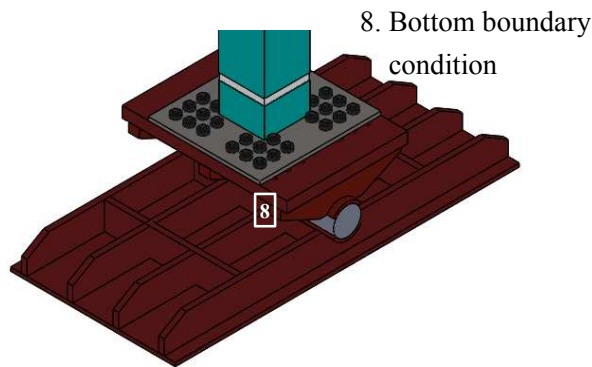
(b) Photo of the test setup



(c) Sketch of top loading device

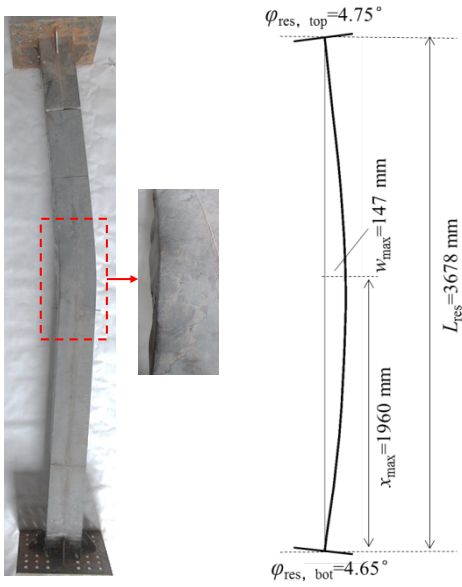


(d) Photo of top loading device

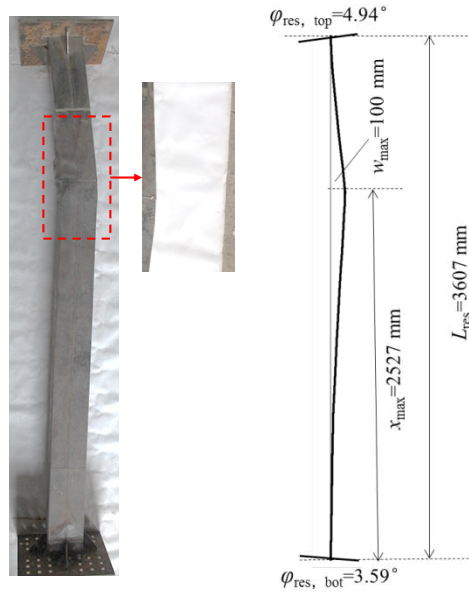


(e) Sketch of bottom loading device

Fig. 4. Test setup and details (unit: mm)



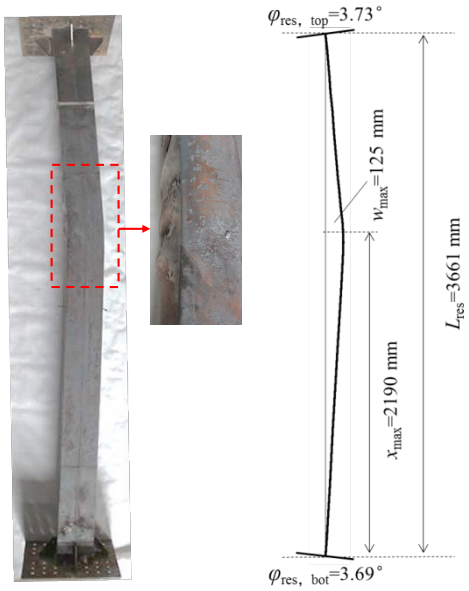
(a) TRC-0.4-0



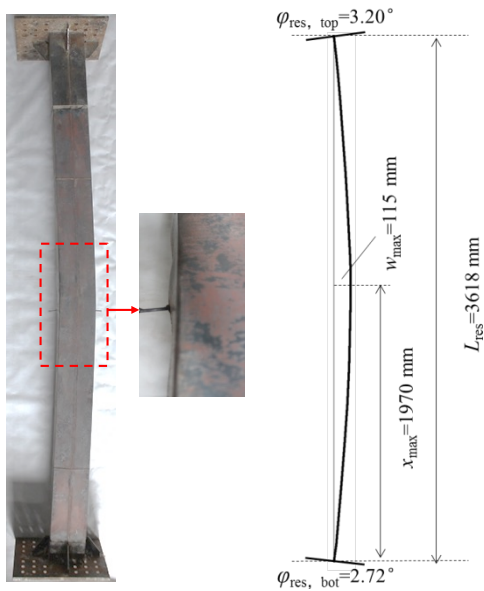
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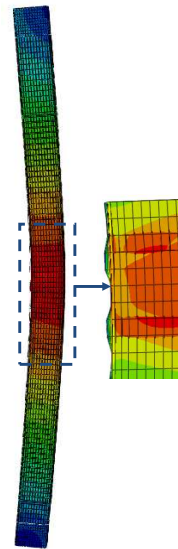
(c) TRC-0.6-0



(d) TRC-0.5-25



(e) TRC-0.5-50





(f) Details of the gaps (TRC-0.4-0)

Fig. 5. Failure modes and residual deformations of tested square TRC slender columns



(a) Overall view (TRC-0.5-25)



(b) Concrete crushing and re-bar buckling in compression zone (TRC-0.5-25)



(c) Concrete cracks in tension zone (TRC-0.5-25)



(d) Overall view (TRC-0.6-0)



(e) Concrete crushing (TRC-0.6-0)



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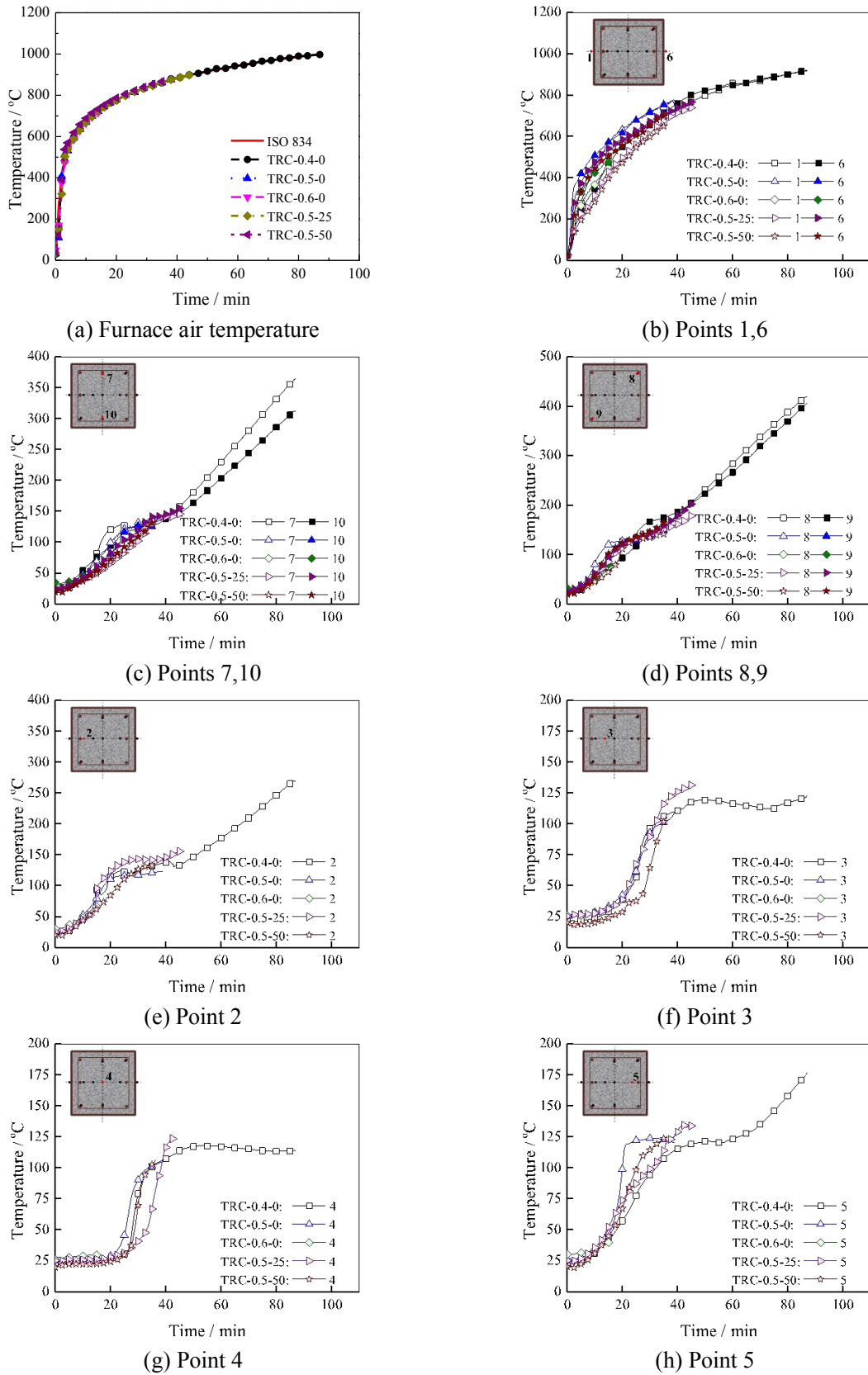
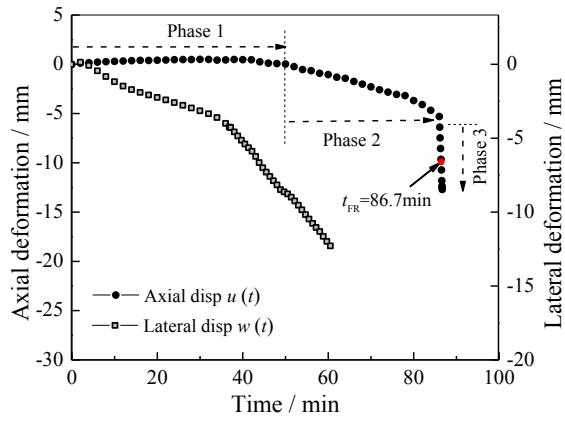
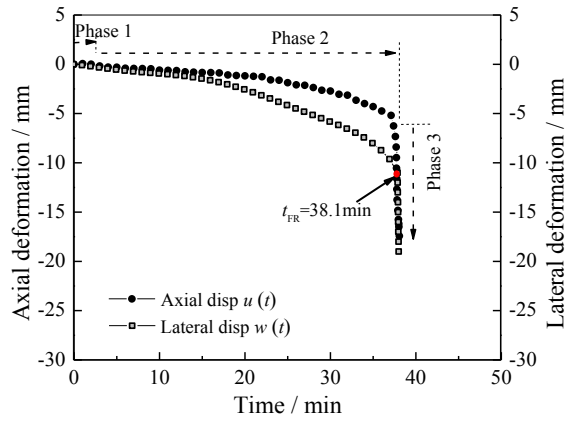


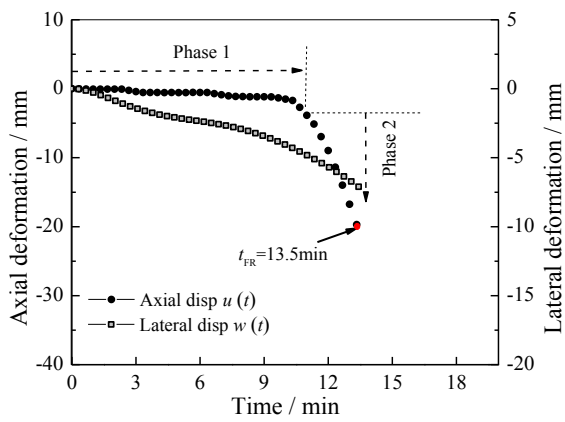
Fig. 7. Furnace air temperatures and uniformity of the temperature fields within the tested specimens



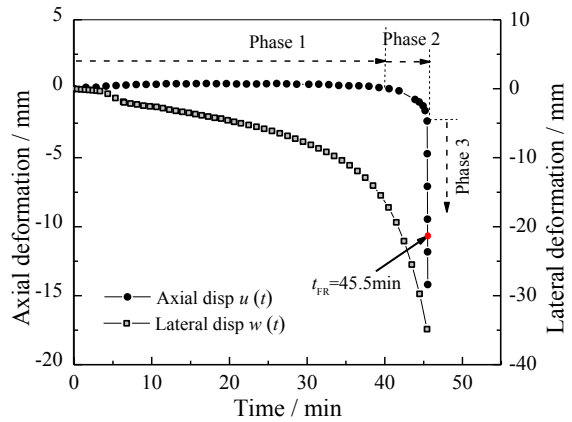
(a) TRC-0.4-0



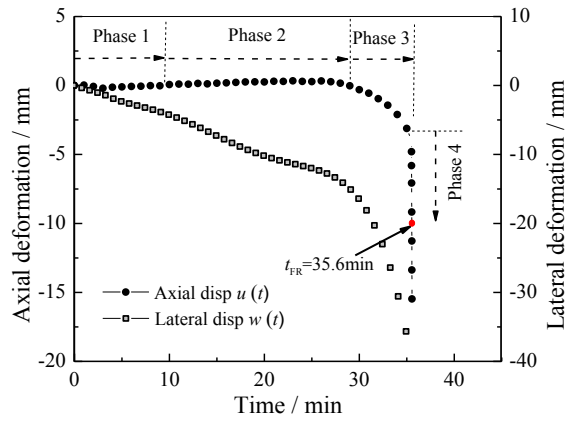
(b) TRC-0.5-0



(c) TRC-0.6-0

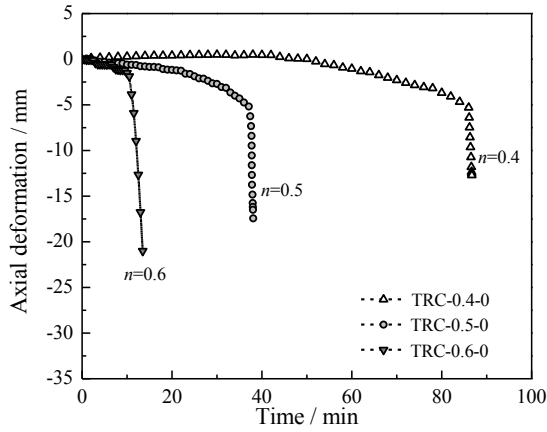


(d) TRC-0.5-25

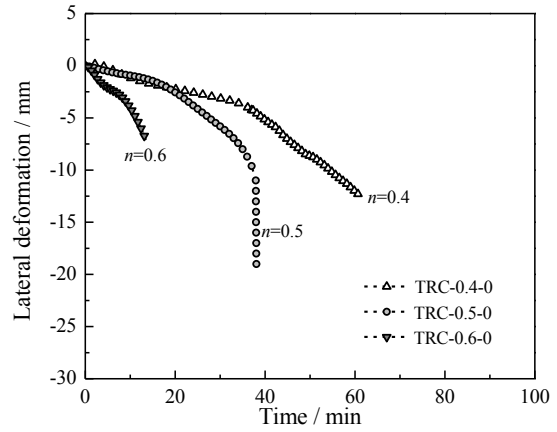


(e) TRC-0.5-50

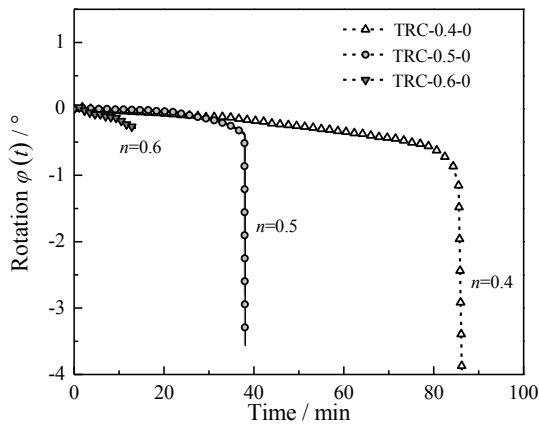
Fig. 8. Axial and lateral deformation-time relationships of tested TRC columns



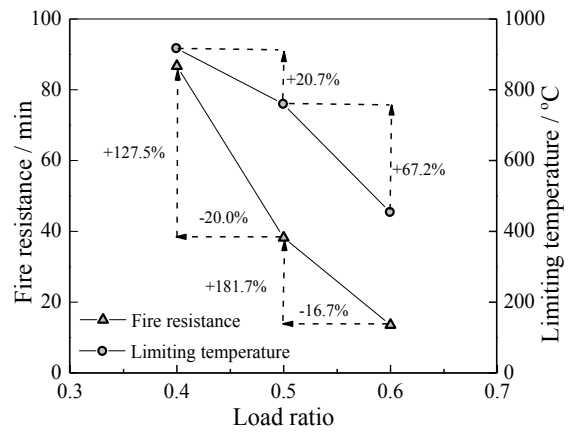
(a) Axial deformation vs load ratio



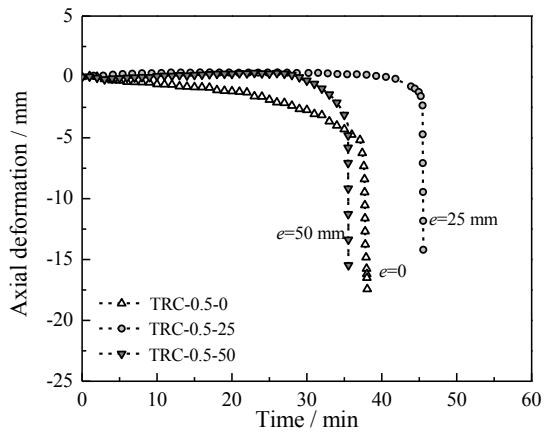
(b) Lateral deformation vs load ratio



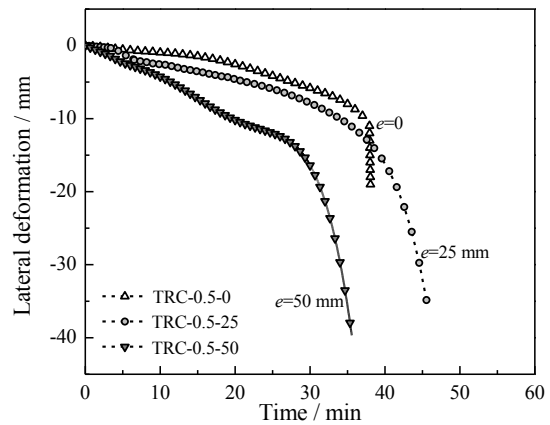
(c) Endplate rotation vs load ratio



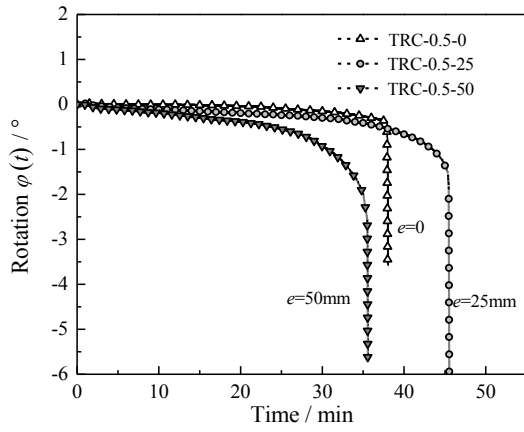
(d) Fire resistance & Limiting temperature vs load ratio



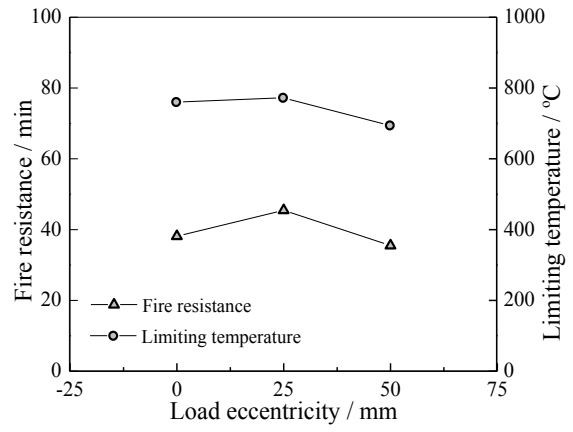
(e) Axial deformation vs load eccentricity



(f) Lateral deformation vs load eccentricity

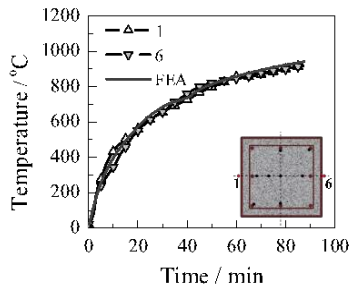


(g) Endplate rotation vs load eccentricity

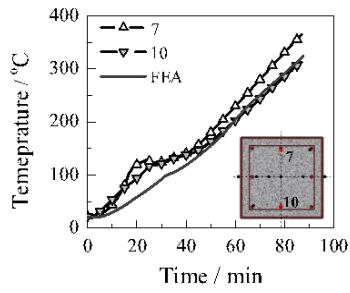


(h) Fire resistance & Limiting temperature vs load eccentricity

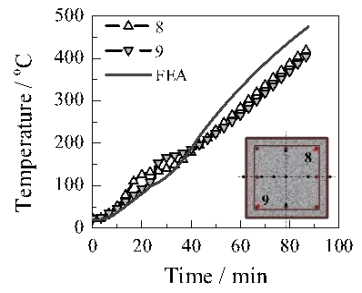
Fig. 9. Influences of load ratio and load eccentricity on the fire performance of test specimens



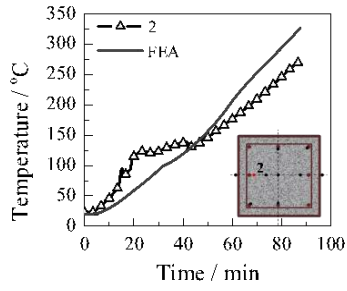
(a) Points 1,6 (TRC-0.4-0)



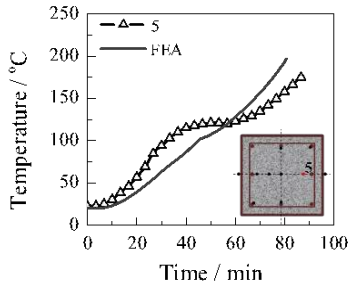
(b) Points 7,10 (TRC-0.4-0)



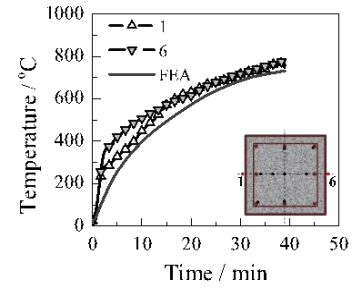
(c) Points 8,9 (TRC-0.4-0)



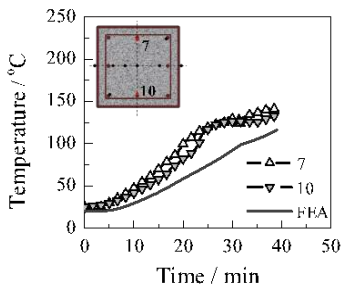
(d) Point 2 (TRC-0.4-0)



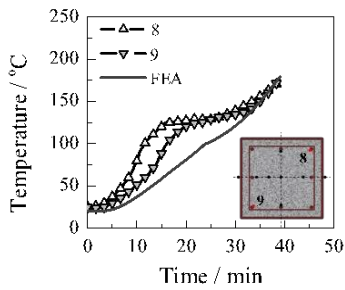
(e) Point 5 (TRC-0.4-0)



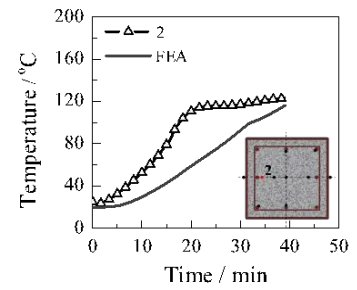
(f) Points 1,6 (TRC-0.5-0)



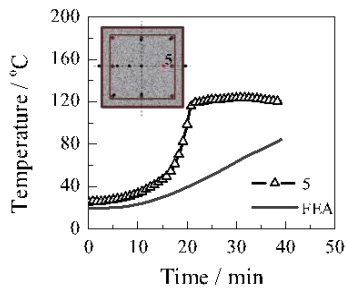
(g) Points 7,10 (TRC-0.5-0)



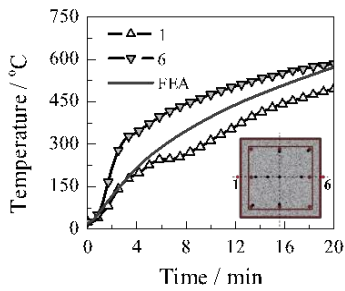
(h) Points 8,9 (TRC-0.5-0)



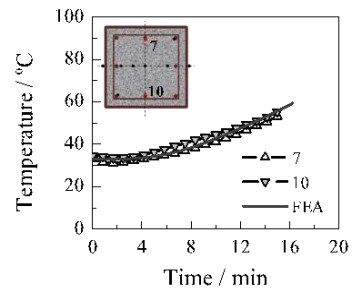
(i) Point 2 (TRC-0.5-0)



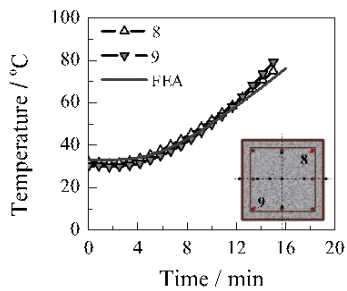
(j) Point 5 (TRC-0.5-0)



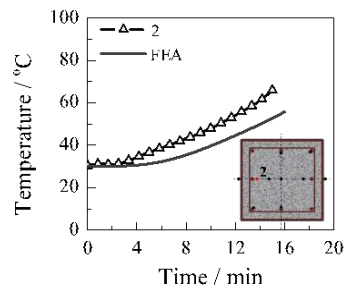
(k) Points 1,6 (TRC-0.6-0)



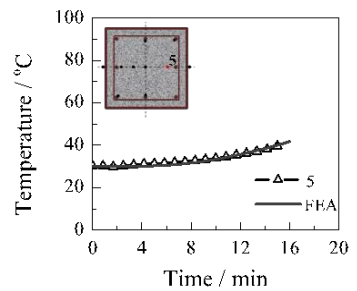
(l) Points 7,10 (TRC-0.6-0)



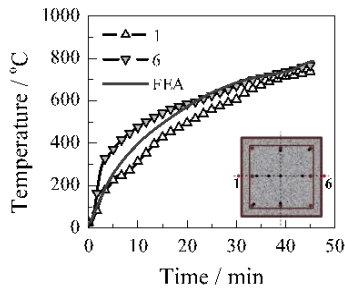
(m) Points 8,9 (TRC-0.6-0)



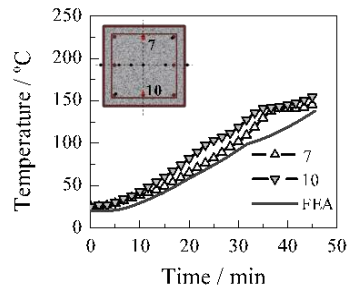
(n) Point 2 (TRC-0.6-0)



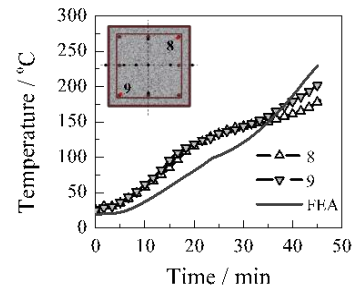
(o) Point 5 (TRC-0.6-0)



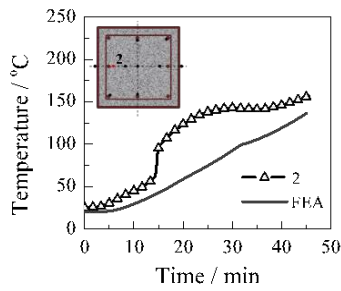
(p) Points 1,6 (TRC-0.5-25)



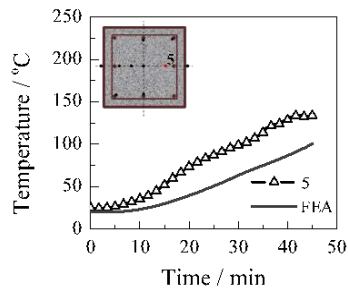
(q) Points 7,10 (TRC-0.5-25)



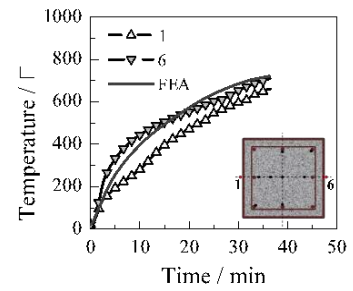
(r) Points 8,9 (TRC-0.5-25)



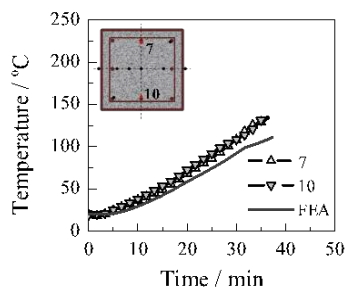
(s) Point 2 (TRC-0.5-25)



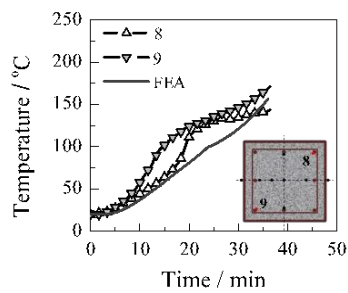
(t) Point 5 (TRC-0.5-25)



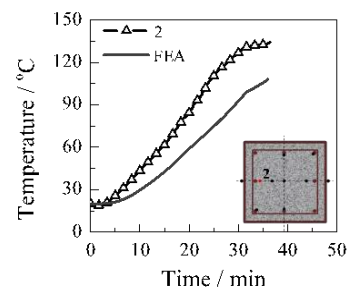
(u) Points 1,6 (TRC-0.5-50)



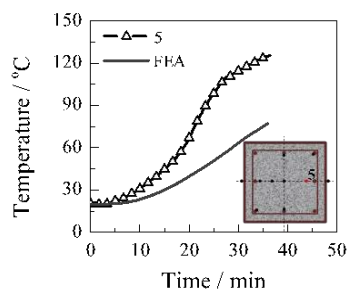
(v) Points 7,10 (TRC-0.5-50)



(w) Points 8,9 (TRC-0.5-50)

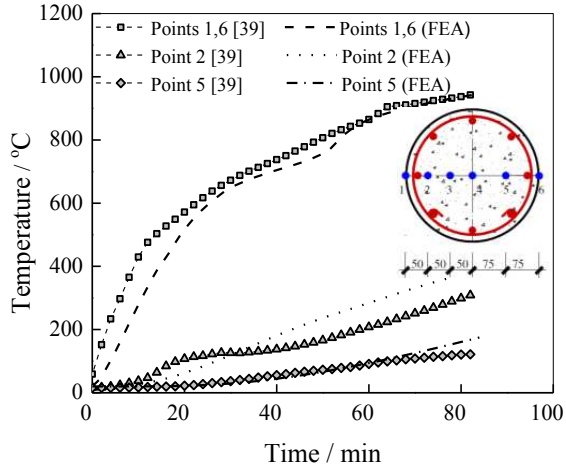


(x) Point 2 (TRC-0.5-50)

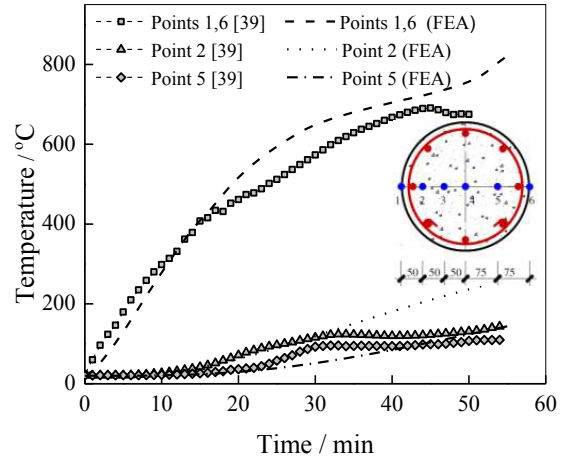


(y) Point 5 (TRC-0.5-50)

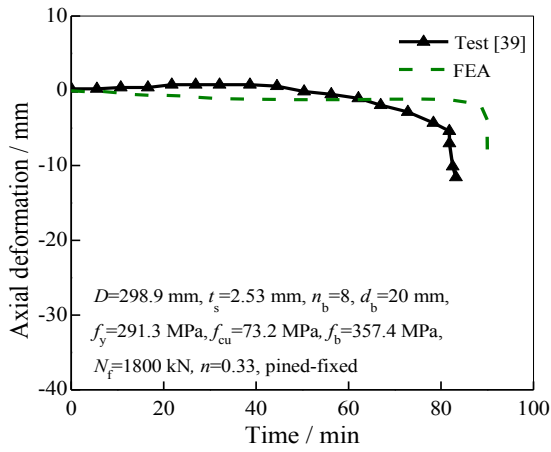
Fig. 10. Comparison of the temperature-time curves given by FEA modelling and experiments conducted in this study



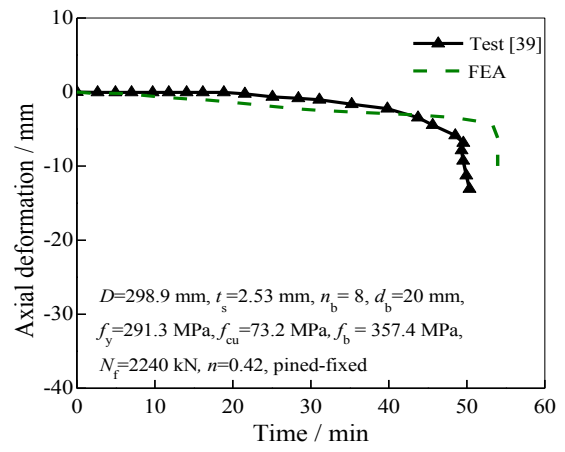
(a) Temperature (STCRC-2)



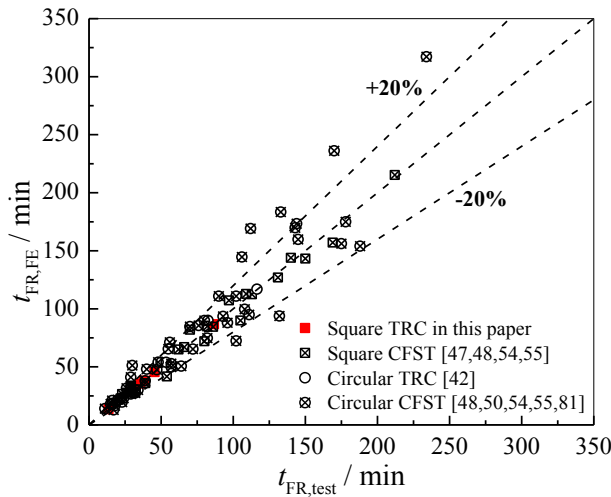
(b) Temperature (STCRC-3)



(c) Axial deformation (STCRC-2)

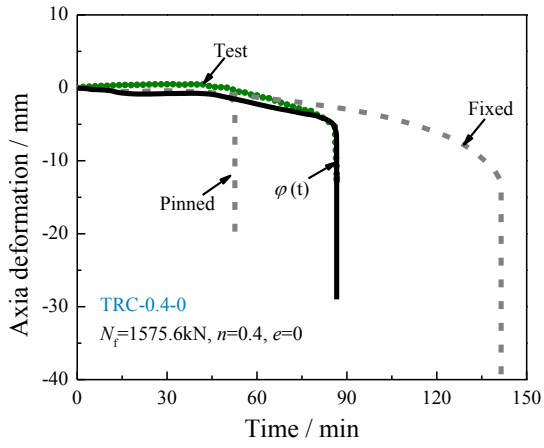


(d) Axial deformation (STCRC-3)

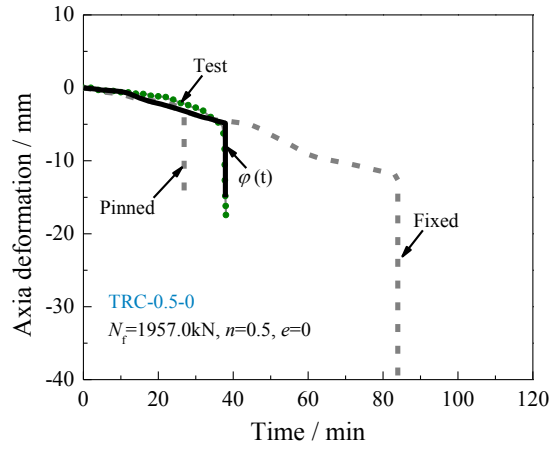


(e) Fire resistance of composite columns

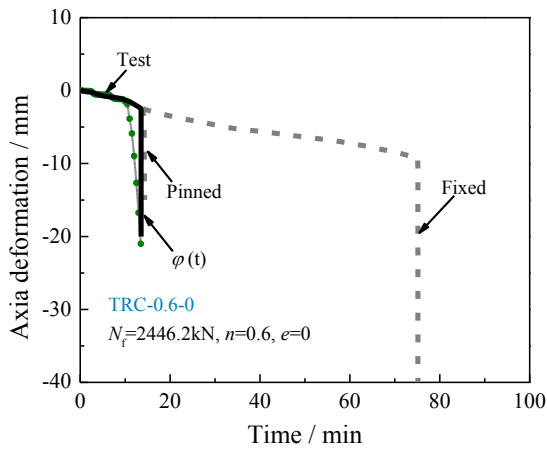
Fig. 11. Validation of the FEA modelling against the experimental results of circular TRC columns and CFST columns conducted by other researchers



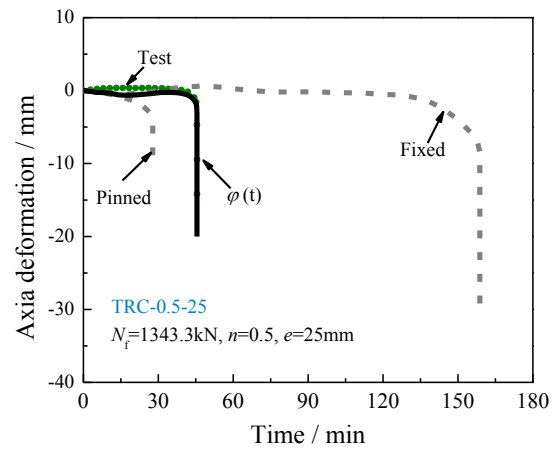
(a) Axial deformation (TRC-0.4-0)



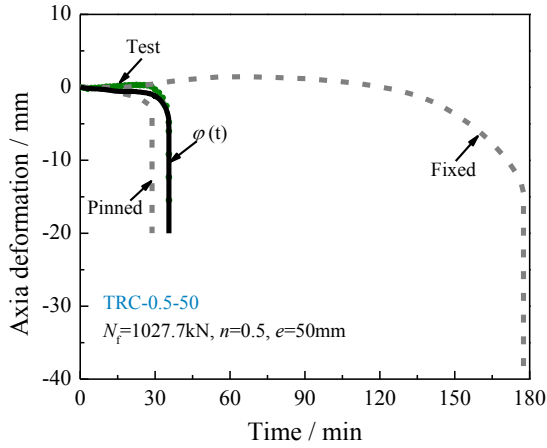
(b) Axial deformation (TRC-0.5-0)



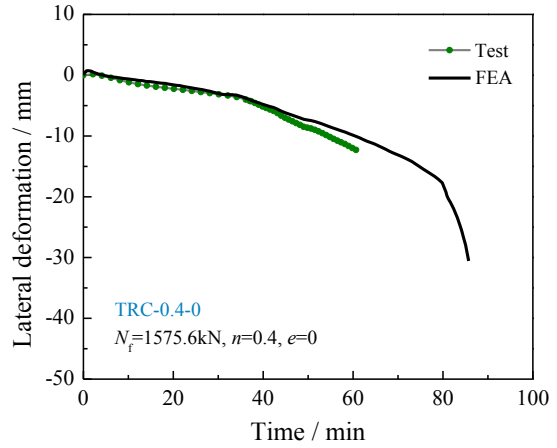
(c) Axial deformation (TRC-0.6-0)



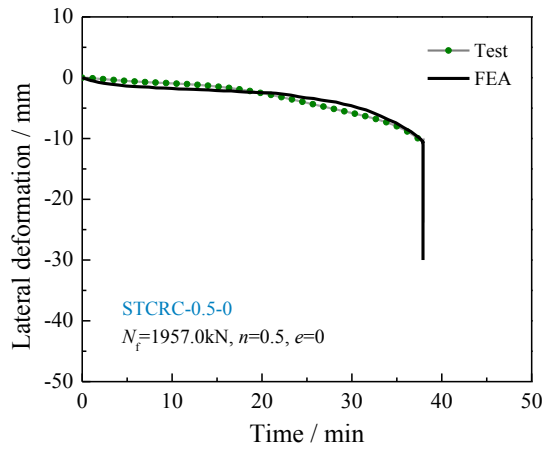
(d) Axial deformation (TRC-0.5-25)



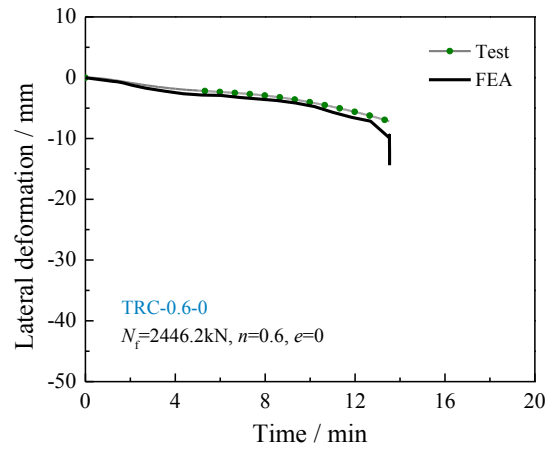
(e) Axial deformation (TRC-0.5-50)



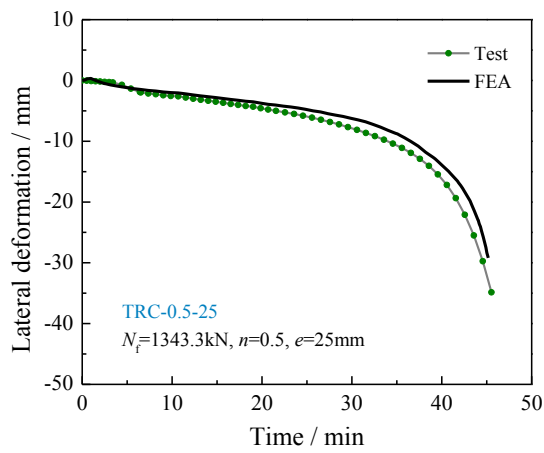
(f) Lateral deformation (TRC-0.4-0)



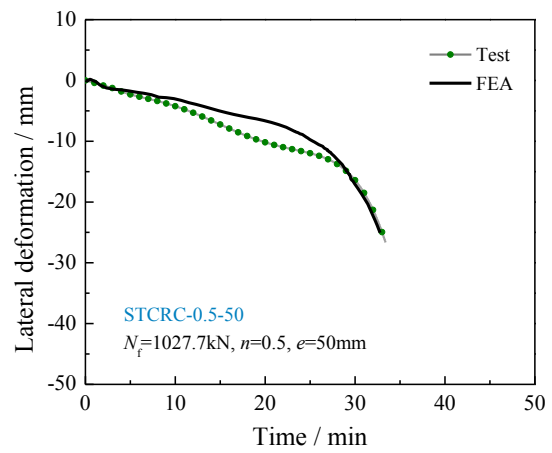
(g) Lateral deformation (TRC-0.5-0)



(h) Lateral deformation (TRC-0.6-0)

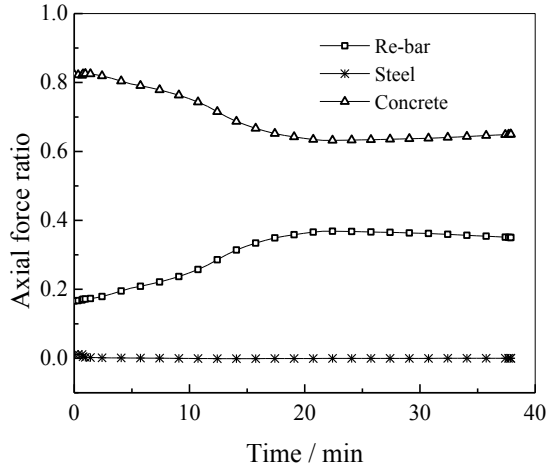


(i) Lateral deformation (TRC-0.5-25)

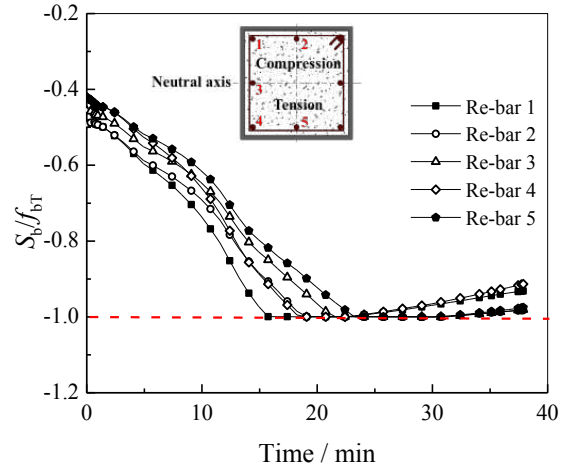


(j) Lateral deformation (TRC-0.5-50)

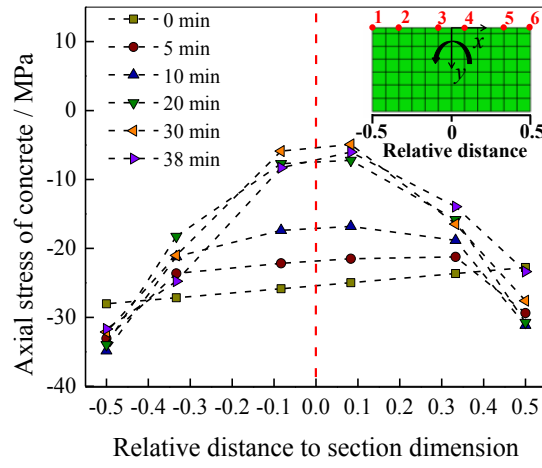
Fig. 12. Axial and lateral deformation-time curves given by the FEA modelling vs experiments conducted in this study



(a) Axial force ratios

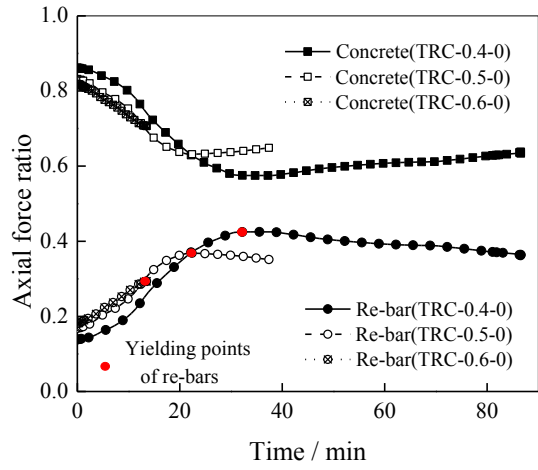


(b) Normalized stress-time curves of re-bars

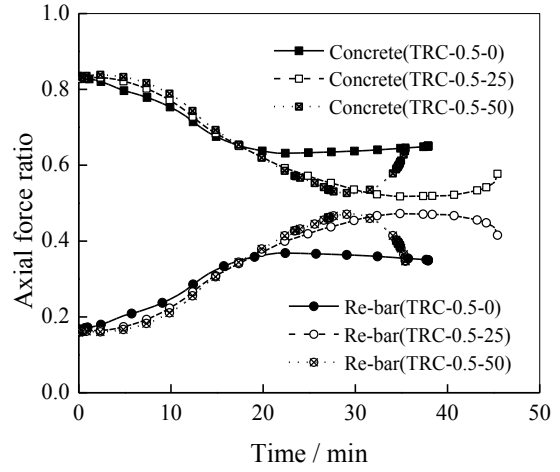


(c) Axial stress distribution of concrete nodes

Fig. 13. Load redistribution and stress evolutions of column TRC-0.5-0

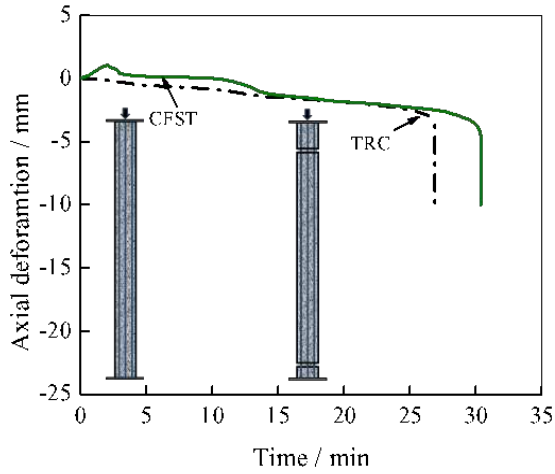


(a) Influence of load ratio

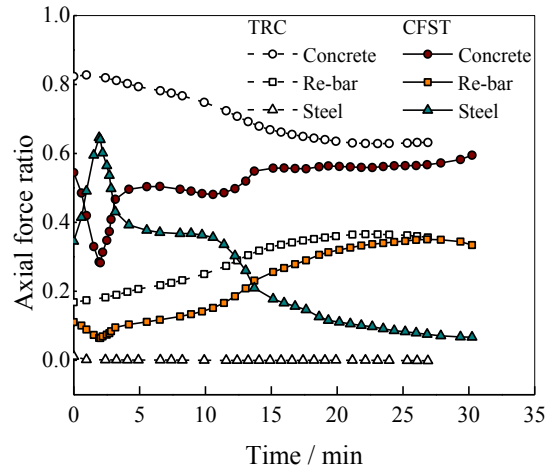


(b) Influence of load eccentricity

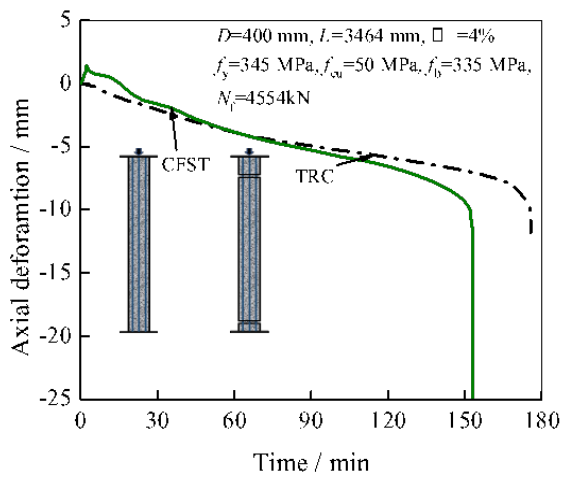
Fig. 14. Load redistribution for the tested square TRC columns



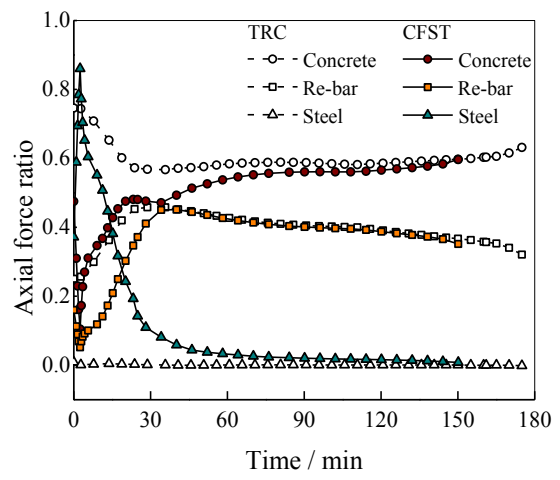
(a) Axial deformation ( $D=250$  mm)



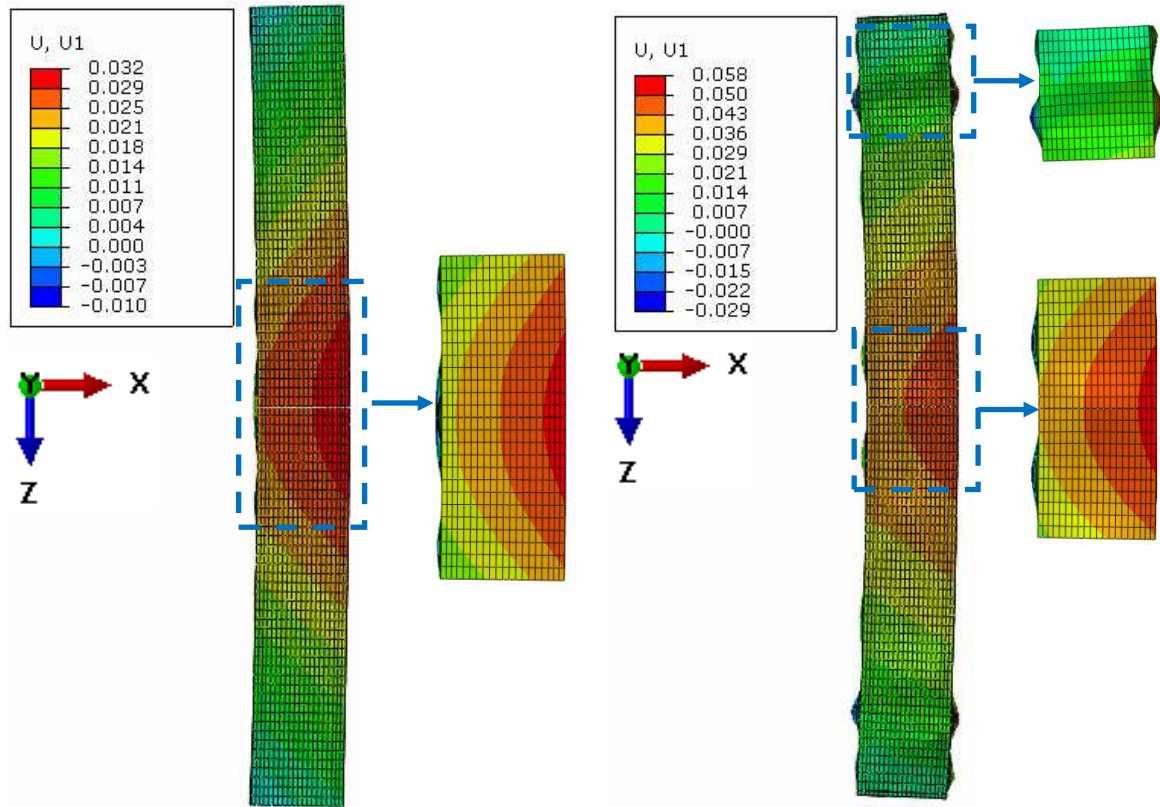
(b) Load redistribution ( $D=250$  mm)



(c) Axial deformation ( $D=400$  mm)



(d) Load redistribution ( $D=400$  mm)



(e) Failure mode of the TRC ( $D=400$  mm)

(f) Failure mode the CFST ( $D=400$  mm)

Fig. 15. Comparison of the fire behaviour between the TRC columns and the CFST columns

Table 1

Typical engineering applications of TRC columns in China

Name	Type	Year	Height or Span (m)	Section shape and dimension (mm)
Harbin Investment Mansion	High-rise building	2010	170	Square (1200 & 1300)
Harbin Technology & Innovation Mansion	High-rise building	2011	200	Square (900)
Dalian PetroChina Mansion	High-rise building	2011	176	Rectangular (900×700 oblique column) (1400×1100 vertical column)
China Resources Xiaojing Bay Hotel	High-rise building	2016	44.6	Rectangular (n.a.)
Qingdao Haitian Centre	High-rise building	2018	210 (T1) 245 (T3)	Circular (1400 & 1500)
Heixiazi Island Dongji Pagoda	Pagoda	2012	81	Circular (1200)
Dalian Gymnasium	Large-span gymnasium	2010	116×140	Rectangular (1800×1000) Circular (1500)
Dandong Olympic Stadium	Large-span stadium	2011	256×288	Circular (1200)
Dalian Stadium	Large-span stadium	2012	320×293	Rectangular (1000×800) Circular (1200)

Table 2

Details of the tested square TRC columns

Specimen name	$D \times B$ (mm)		$t_s$ (mm)		$L$ (mm)	$\alpha$ (%)	$\rho$ (%)	$e$ (mm)	$n$	$N_f$ (kN)	$t_{FR}$ (min)
	Nominal	Measured	Nominal	Measured							
TRC-0.4-0	250×250	251.3×250.6	2.2	2.19	3810	3.62	2.67	0	0.4	1575.6	86.7
TRC-0.5-0	250×250	251.9×251.5	2.2	2.17	3810	3.62	2.67	0	0.5	1957.1	38.1
TRC-0.6-0	250×250	251.7×251.4	2.2	2.21	3810	3.62	2.67	0	0.6	2446.2	13.5
TRC-0.5-25	250×250	251.3×250.6	2.2	2.18	3810	3.62	2.67	25	0.5	1343.3	45.5
TRC-0.5-50	250×250	252.1×250.7	2.2	2.19	3810	3.62	2.67	50	0.5	1027.7	35.6

Table 3

Mechanical properties of steel tube and re-bars at ambient temperature

	$\phi$ or $t_s$ (mm)	$f_y$ or $f_b$ (MPa)	$f_u$ (MPa)	$E_s$ ( $10^5$ MPa)	$\nu$	$\epsilon_f$ (%)
Re-bar-16	15.65	441.33	626.41	2.05	0.29	17.71
Stirrup-10	9.87	361.00	574.96	2.09	0.30	19.61
Stirrup-8	7.95	343.25	562.17	2.04	0.30	25.63
Steel tube	2.18	280.72	442.94	2.06	0.30	40.83

Table 4

Mix proportions and mechanical properties of the SCC

Cement (kg/m <sup>3</sup> )	Mineral powder (kg/m <sup>3</sup> )	Fly ash (kg/m <sup>3</sup> )	Expanding agent (kg/m <sup>3</sup> )	Medium sand (kg/m <sup>3</sup> )	Coarse aggregate (kg/m <sup>3</sup> )	Water (kg/m <sup>3</sup> )	Superplasticizer (kg/m <sup>3</sup> )	$f_{cu,28}$ (MPa)	$f_{cu,test}$ (MPa)	$E_{c,28}$ (10 <sup>4</sup> MPa)	$E_{c,test}$ (10 <sup>4</sup> MPa)	Moisture content (%)	Concrete age (day)
210	100	100	40	800	900	185	11	31.53	50.95	2.81	3.88	5.4	190

Table 5

Details of the fire tests of TRC and CFST columns

Reference	Column Type	Column No.	$D$ (mm)	$t_s$ (mm)	$L$ (m)	Re-bars	$e$ (mm)	$f_y$ (MPa)	$f_c'$ (MPa)	$f_b$ (MPa)	$N_f$ (kN)	$t_{FR,test}$ (min)	$t_{FR,FE}$ (min)	$t_{FR,FE}/t_{FR,test}$
This paper	Square TRC	TRC-0.4-0	250	2.2	3.81	8 $\phi$ 16	0	280.7	40.8	441.33	1576	86.7	86.7	1.00
	Square TRC	TRC-0.5-0	250	2.2	3.81	8 $\phi$ 16	0	280.7	40.8	441.33	1957	38.1	38.1	1.00
	Square TRC	TRC-0.6-0	250	2.2	3.81	8 $\phi$ 16	0	280.7	40.8	441.33	2446	13.5	13.5	1.00
	Square TRC	TRC-0.5-25	250	2.2	3.81	8 $\phi$ 16	25	280.7	40.8	441.33	1343	45.5	45.5	1.00
	Square TRC	TRC-0.5-50	250	2.2	3.81	8 $\phi$ 16	50	280.7	40.8	441.33	1028	35.6	35.6	1.00
Ref. [42]	Circular TRC	STCRC-1	300	2.53	3.81	8 $\phi$ 20	0	291.3	58.6	357.4	1340	116.5	116.9	1.00
	Circular TRC	STCRC-2	300	2.53	3.81	8 $\phi$ 20	0	291.3	58.6	357.4	1800	82.5	90	1.09
	Circular TRC	STCRC-3	300	2.53	3.81	8 $\phi$ 20	0	291.3	58.6	357.4	2240	50	53.9	1.08
	Circular TRC	STCRC-4	300	2.53	3.81	8 $\phi$ 20	0	291.3	58.6	357.4	2240	53.5	53.9	1.01
Ref. [47]	Square CFST	SP-1	219	5.3	3.81	-	0	246	15	-	950	169	157	0.93
	Square CFST	SP-2	350	7.7	3.81	-	0	284	15	-	2700	140	144	1.03
	Square CFST	SP-3	350	7.7	3.81	-	52.5	284	15	-	1670	109	112.8	1.03
Ref. [48]	Square CFST	S1	150	8	3.18	4 $\phi$ 12	75	452.7	45	548	161.1	26	27.7	1.07
	Square CFST	S2	220	10	3.18	4 $\phi$ 16+4 $\phi$ 10	110	560.3	39.7	527( $\phi$ 16) 575.3( $\phi$ 10)	446.5	23	26.5	1.15
	Square CFST	S3	150	8	3.18	4 $\phi$ 12	0	452.7	43.2	548	404.3	32	28	0.88
	Square CFST	S4	220	10	3.18	4 $\phi$ 16+4 $\phi$ 10	0	560.3	42.4	527( $\phi$ 16) 575.3( $\phi$ 10)	882.9	54	41.7	0.77
	Square CFST	S5	150	8	3.18	8 $\phi$ 12	112.5	452.7	48.7	548	133.2	29	31.4	1.08
	Square CFST	S6	220	10	3.18	4 $\phi$ 20+4 $\phi$ 16	110	560.3	38.8	576( $\phi$ 20) 527( $\phi$ 16)	452.6	29	33.8	1.17
	Circular CFST	C1	193.7	8	3.18	6 $\phi$ 12	96.9	359.1	36.4	512.4	186.7	26	31.6	1.22
	Circular CFST	C2	273	10	3.18	6 $\phi$ 16	136.5	369.7	37.6	553.5	387.5	30	51.2	1.71
	Circular CFST	C3	193.7	8	3.18	6 $\phi$ 12	0	359.1	43.2	512.4	535.6	29	26.5	0.91

Table 5 (cont'd) Details of the fire tests of TRC and CFST columns

Reference	Column Type	Column No.	$D$ (mm)	$t_s$ (mm)	$L$ (m)	Re-bars	$e$ (mm)	$f_y$ (MPa)	$f_c'$ (MPa)	$f_b$ (MPa)	$N_f$ (kN)	$t_{FR,test}$ (min)	$t_{FR,FE}$ (min)	$t_{FR,FE}/t_{FR,test}$
Ref. [48]	Circular CFST	C4	273	10	3.18	6 $\phi$ 16	0	451.1	37.8	553.5	882.9	72	65.3	0.91
	Circular CFST	C5	193.7	8	3.18	6 $\phi$ 16	145.3	359.1	35.8	553.5	152.4	29	41	1.41
	Circular CFST	C6	273	10	3.18	8 $\phi$ 20	136.5	369.7	36.9	566.5	391.5	57	49.8	0.87
Ref. [50]	Circular CFST	C159-6-3-30-20-20	159	6	3.18	-	20	332	35.8	-	169	32	27.52	0.86
	Circular CFST	C159-6-3-30-20-40	159	6	3.18	-	20	332	42.2	-	337	16	21	1.31
	Circular CFST	C159-6-3-90-20-20	159	6	3.18	-	20	332	73.7	-	272	34	30.12	0.89
	Circular CFST	C159-6-3-90-20-40	159	6	3.18	-	20	342.6	74.6	-	544	11	14	1.27
	Circular CFST	C159-6-3-30-50-20	159	6	3.18	-	50	343.6	30.5	-	126.4	29	32.5	1.12
	Circular CFST	C159-6-3-30-50-40	159	6	3.18	-	50	365.7	38.3	-	252.8	23	19.55	0.85
	Circular CFST	C159-6-3-90-50-20	159	6	3.18	-	50	365.7	79.1	-	194	30	28.4	0.95
	Circular CFST	C159-6-3-90-50-40	159	6	3.18	-	50	365.7	98.3	-	388	16	18.5	1.16
	Circular CFST	RC159-6-3-30-20-20	159	6	3.18	4 $\phi$ 12	20	357.2	39	500	180	47	47.5	1.01
	Circular CFST	RC159-6-3-30-20-40	159	6	3.18	4 $\phi$ 12	20	357.2	40.4	500	360	24	23	0.96
	Circular CFST	RC159-6-3-90-20-20	159	6	3.18	4 $\phi$ 12	20	357.2	93.7	500	263.8	48	54	1.13
	Circular CFST	RC159-6-3-90-20-40	159	6	3.18	4 $\phi$ 12	20	386.4	96	500	527.7	22	22.8	1.04
	Circular CFST	RC159-6-3-30-50-20	159	6	3.18	4 $\phi$ 12	50	386.4	31	500	140	39	38	0.97
	Circular CFST	RC159-6-3-30-50-40	159	6	3.18	4 $\phi$ 12	50	386.4	39.5	500	279.9	20	21.6	1.08
	Circular CFST	RC159-6-3-90-50-20	159	6	3.18	4 $\phi$ 12	50	315.2	93	500	203.7	40	48	1.20
	Circular CFST	RC159-6-3-90-50-40	159	6	3.18	4 $\phi$ 12	50	315.2	91.9	500	407.4	15	18	1.20
Ref. [54]	Square CFST	SQ-1	152.4	6.35	3.81	-	0	350	58.3	-	376	66	67	1.02
	Square CFST	SQ-2	152.4	6.35	3.81	-	0	350	46.5	-	286	80	72.01	0.90
	Square CFST	SQ-7	177.8	6.35	3.81	-	0	350	57	-	549	86	84.5	0.98
	Square CFST	SQ-17	254	6.35	3.81	-	0	350	58.3	-	1096	62	65	1.05
	Square CFST	SQ-20	254	6.35	3.81	-	0	350	46.5	-	931	97	107.2	1.11
	Square CFST	SQ-24	304.8	6.35	3.81	-	0	350	58.8	-	1130	131	127	0.97

Table 5 (cont'd) Details of the fire tests of TRC and CFST columns

Reference	Column Type	Column No.	$D$ (mm)	$t_s$ (mm)	$L$ (m)	Re-bars	$e$ (mm)	$f_y$ (MPa)	$f_c'$ (MPa)	$f_b$ (MPa)	$N_f$ (kN)	$t_{FR,test}$ (min)	$t_{FR,FE}$ (min)	$t_{FR,FE}/t_{FR,test}$
Ref. [54]	Circular CFST	C-02	141.3	6.55	3.81	-	0	350	33.1	-	110	55	65.4	1.19
	Circular CFST	C-04	141.3	6.55	3.81	-	0	350	31	-	131	57	52.8	0.93
	Circular CFST	C-05	168.3	4.78	3.81	-	0	350	32.7	-	150	76	85.6	1.13
	Circular CFST	C-08	168.3	4.78	3.81	-	0	350	35.5	-	218	56	71.1	1.27
	Circular CFST	C-11	219.1	4.78	3.81	-	0	350	31	-	492	80	89.9	1.12
	Circular CFST	C-13	219.1	4.78	3.81	-	0	350	32.3	-	384	102	110.9	1.09
	Circular CFST	C-17	219.1	8.18	3.81	-	0	350	31.7	-	525	82	84.9	1.04
	Circular CFST	C-20	273.1	5.56	3.81	-	0	350	28.6	-	574	112	169.1	1.51
	Circular CFST	C-21	273.1	5.56	3.81	-	0	350	29	-	525	133	183.4	1.38
	Circular CFST	C-22	273.1	5.56	3.81	-	0	350	27.2	-	1000	70	84.7	1.21
	Circular CFST	C-23	273.1	12.7	3.81	-	0	350	27.4	-	525	143	169.8	1.19
	Circular CFST	C-25	323.9	6.35	3.81	-	0	350	27.6	-	699	145	159.8	1.10
	Circular CFST	C-26	323.9	6.35	3.81	-	0	350	24.3	-	1050	93	93.4	1.00
	Circular CFST	C-29	355.6	12.7	3.81	-	0	350	25.4	-	1050	170	236.2	1.39
	Circular CFST	C-31	141.3	6.55	3.81	-	0	300	30.2	-	80	82	74.8	0.91
	Circular CFST	C-32	141.3	6.55	3.81	-	0	300	34.8	-	143	64	50.6	0.79
	Circular CFST	C-34	219.1	4.78	3.81	-	0	300	35.4	-	500	111	94.9	0.85
	Circular CFST	C-35	219.1	4.78	3.81	-	0	300	42.7	-	560	108	99.6	0.92
	Circular CFST	C-37	219.1	8.18	3.81	-	0	300	28.7	-	560	102	72.4	0.71
	Circular CFST	C-40	273.1	6.35	3.81	-	0	300	46.5	-	1050	106	144.6	1.36
Circular CFST	C-42	273.1	6.35	3.81	-	0	300	55.4	-	1050	90	110.9	1.23	
Circular CFST	C-44	273.1	6.35	3.81	-	0	300	38.7	-	715	178	175	0.98	
Circular CFST	C-45	273.1	6.35	3.81	-	0	300	38.2	-	712	144	173.4	1.20	
Circular CFST	C-50	323.9	6.35	3.81	-	0	300	42.4	-	820	234	317.2	1.36	

Table 5 (cont'd) Details of the fire tests of TRC and CFST columns

Reference	Column Type	Column No.	$D$ (mm)	$t_s$ (mm)	$L$ (m)	Re-bars	$e$ (mm)	$f_y$ (MPa)	$f_c'$ (MPa)	$f_b$ (MPa)	$N_f$ (kN)	$t_{FR,test}$ (min)	$t_{FR,FE}$ (min)	$t_{FR,FE}/t_{FR,test}$
Ref. [55]	Square CFST	SQ-12	203.2	6.35	3.81	4 $\phi$ 16	0	350	47	400	500	150	143.3	0.96
	Square CFST	SQ-13	203.2	6.35	3.81	4 $\phi$ 16	0	350	47	400	930	105	89.92	0.86
	Square CFST	SQ-18	254	6.35	3.81	4 $\phi$ 19.5	0	350	48.1	400	1440	113	112.5	1.00
	Square CFST	SQ-19	254	6.35	3.81	4 $\phi$ 19.5	0	350	48.1	400	2200	70	82	1.17
	Square CFST	SQ-22	304.8	6.35	3.81	4 $\phi$ 16+4 $\phi$ 19.5	0	350	47	400	3400	39	35.94	0.92
	Square CFST	SQ-23	304.8	6.35	3.81	4 $\phi$ 25.2	0	350	47	400	2000	212	215.3	1.02
	Circular CFST	C-48	273.1	6.35	3.81	4 $\phi$ 19.5	0	350	46.7	400	1050	188	154	0.82
Ref. [81]	Circular CFST	C-49	273.1	6.35	3.81	4 $\phi$ 19.5	0	350	47	400	1900	96	88	0.92
	Circular CFST	C1-1	478	8	3.81	-	0	293	31.7	-	4700	29	31.6	1.09
	Circular CFST	C1-2	478	8	3.81	-	71.7	293	31.7	-	2200	32	30.3	0.95
	Circular CFST	C2-1	219	5	3.81	-	32.9	293	31.7	-	450	17	12.9	0.76
	Circular CFST	C2-2	219	5	3.81	-	65.7	293	31.7	-	300	18	16.5	0.92
	Circular CFST	C2-3	219	5	3.81	-	0	293	31.7	-	960	132	93.8	0.71
	Circular CFST	C2-4	219	5	3.81	-	0	293	31.7	-	960	175	156.1	0.89
												Mean	1.05	
												Std. dev.	0.18	

Notes: “ $D$ ” width of the square section or diameter of the circular section; “ $t_s$ ” steel tube thickness; “ $L$ ” whole column length; “ $\phi$ ” diameter of the reinforcing bar; “ $e$ ” load eccentricity; “ $f_y$ ” steel tube yield strength; “ $f_c'$ ” concrete cylinder compressive strength; “ $f_b$ ” reinforcing bar yield strength; “ $N_f$ ” applied axial load in fire test; “ $t_{FR,test}$ ” tested fire resistance; “ $t_{FR,FE}$ ” FEA predicted fire resistance.