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# Dynamic Response of Cross Steel Reinforced Concrete Filled Steel Tubular Columns under Impact under Fire

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## Abstract:

To explore the impact response of cross steel-reinforced concrete-filled steel tubular (CSRCFST) columns under fire, a finite element model using ABAQUS software was generated. After validation against test results, parametric studies were carried out to investigate the effects of impact load as well as time of fire exposure on the impact resistance of CSRCFST columns. The numerical results show that the impact behavior of post-fire CSRCFST columns can be divided into three stages: peak stage, plateau stage, and softening stage. For CSRCFST columns, the peak and plateau stages are important, which absorbed 32.4 % and 67.6 % of the impact kinetic energy, respectively. After two hours of fire exposure, the stiffness and peak impact load of the column decreased by 93.7 % and 71.7 %, respectively. However, the peak mid-span deflection and residual deflection increased by 6.5 % and 20.1 %, respectively. When the drop weight tripled, the maximum deflection and residual deformation of the midspan increased by 2.8 and 3.2 times, respectively. However, the peak impact load increases only by 14.5 %. When the impact energy is the similar, the maximum midspan deflection of the specimen is almost identical, whereas a larger impact momentum reduces the peak

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23 impact force but increases the impact force at the plateau stage. By increasing fire duration, the  
24 behaviors of the column deteriorate seriously, with 85% reductions in peak impact force and 39%  
25 increase in maximum midspan deflection. In addition, the effects of impact velocity are also  
26 significant regarding each stage.

27 **Keywords:** CSRCFST; Post-fire; Impact behavior; Numerical simulation; Column

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## 29 **1 Introduction**

30 Accidental loads such as explosion, fire, and vehicular impact may cause partial destruction of  
31 the building structure and lead to a disproportionate collapse of the whole structure [1, 2], bringing  
32 serious consequences. Therefore, studies on the progressive collapse behavior of structures are  
33 needed [3-8]. The engineering practice shows that the building structure is often accompanied by  
34 subsequent impact load when fire occurs. For example, in 2001, the Twin Towers of the World Trade  
35 Center in the United States collapsed progressively after being hit by a passenger plane hijacked by  
36 terrorists, causing serious casualties. Subsequent studies show that the large area fire caused by  
37 aircraft impact is the main reason that resulted in the collapse of that building [9, 10]. Therefore, it is  
38 essential to study the progressive collapse behavior of building structures under the coupling action  
39 of fire and impact.

40 Wang et al. [11] proposed a new type of composite structure, namely Cross Steel Reinforced  
41 Concrete Filled Steel Tubular (CSRCFST) structure based on its structure with good compressive,  
42 flexural, and shear bearing capacity and deformation capacity [12, 13] but relatively poor fire  
43 resistance [11], as shown in Fig. 1. At present, many scholars have carried out relevant studies on the

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44 fire resistance and impact resistance of Concrete Filled Steel Tubular (CFST) and CSRCFST  
45 structures, respectively. Wang et al. [14] conducted an experimental study on CFST components  
46 under the horizontal impact, and the study showed that axial load could improve the impact  
47 performance of components to a certain extent. Han et al. [15] studied the impact resistance of high-  
48 strength CFST members by experimental research and numerical simulation and proposed a  
49 simplified model for calculating dynamic flexural bearing capacity of CFST members based on the  
50 results. Rifaie et al. [16] investigated the structural behavior of CFST columns connected by long  
51 bolts and end plates under horizontal impact load. The results showed that when thicker end-plate  
52 was used the impact resistance of CFST columns would be weakened, the fracture of bolts would be  
53 accelerated, and the energy consumption would be reduced. Zhu et al. [17] studied the impact  
54 behavior of CSRCFST columns under different impact velocity, height, axial load, steel tube  
55 thickness, and boundary conditions. It was found that the external square steel tube can effectively  
56 protect the internal concrete, and the steel tube was the main energy dissipation source of the structure.  
57 Li et al. [18] conducted a study on the surface thermal emissivity and thermal response of CFST  
58 columns in high temperature environment, and it showed that the smaller the surface thermal  
59 emissivity of the columns, the better the fire resistance of the structure. Li et al. [19] studied the fire  
60 resistance limit of CFST columns under different variable parameters such as steel yield strength,  
61 concrete compressive strength, and the thickness of the fire protection layer of lightweight aggregate  
62 concrete. The results showed that lightweight aggregate concrete can effectively improve the fire  
63 resistance of columns. Wang et al. [20] carried out experimental and numerical studies to figure out  
64 the effects of initial geometrical defects, residual stress, multi-factor coupling, and other variable  
65 parameters on the fire response characteristics of CFST columns. The results showed that the core

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66 concrete can effectively reduce the specific heat and maximum temperature of the external steel tube,  
67 and the initial geometric defects will produce load eccentricity on CFST columns, reducing its fire  
68 resistance. Ji et al. [21] studied the lateral impact performance of post-fire CSRCFST components.  
69 The designed variables are fire duration, drop hammer to columns mass ratio and axial compression  
70 ratio. The results showed that the maximum mid-span deflection of the column increased by 41 %  
71 and the impact force plateau decreased by 27 % after exposure to fire for 3 hours. The energy absorbed  
72 by the plastic deformation of the steel tube accounted for about 72 % of the whole column.

73 To sum up, there are relatively few studies on impact behavior of CSRCFST structures at present.  
74 Most of the available studies are only considering single action, fire or impact load, and there are few  
75 studies on the coupling action of fire and impact.

76 Therefore, based on the CSRCFST structure proposed by Wang et al. [11] and the impact test at  
77 room temperature conducted by Zhu et al. [17], this paper deeply studied the impact dynamic behavior  
78 of CSRCFST columns under fire by using finite element (FE) analysis method. The specific research  
79 technical route of this paper is as follows. Firstly, the impact test at room temperature is simulated  
80 and verified. On the basis of verifying the validity of the model, the impact dynamic performance of  
81 the column under fire is further studied. Finally, the variable parameters such as impact mass and  
82 impact momentum are expanded and analyzed. It provides necessary helps for design engineers to  
83 design CSRCFST columns considering the coupling effects of fire and impact.

## 84 **2 FE Modeling and verification**

### 85 2.1 Introduction to the program of the validation tests

86 The impact tests conducted by Zhu et al. [17] in room temperature is shown in Fig. 2. Ultra-

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87 heavy drop hammer was adopted, with a total mass of 1158.7 kg, a hammer head size of 300×300×200  
88 mm<sup>3</sup>, and an impact contact surface between the bottom of the hammer head and the column of  
89 300×300 mm<sup>2</sup>. The fixed support consisted of a bottom and a top head and was bolted to a rigid  
90 platform. When the axial force was applied, it was first applied on the disc springs through a 200-Ton  
91 hydraulic jack fixed on the reaction frame, and then the axial force was transmitted to the column  
92 through the disc spring. At the same time, the right end of the columns was reserved for 25 mm  
93 extended support. The total column length was 1800 mm and the cross-section was 300×300 mm<sup>2</sup>.  
94 Moreover, the thickness of the outer steel tube was 8 mm. 225 mm and 350 mm lengths on the left  
95 and right sides of the column were reserved for fixed supports, so the effective length of the column  
96 was 1200 mm. The dimensions of cross-shaped steel profiles inside the column was 200×100×6×9  
97 mm. To make the force uniform and prevent the column from local deformation under axial load, a  
98 steel plate with width of 300 mm, and a thickness of 20 mm was added at both ends of the column.  
99 The column reinforcement details and dimensions are shown in Fig. 3.

100 In the fire test conducted by Zhu et al. [22], the electric heating furnace device was used to heat  
101 up the three surfaces of the CSRCFST columns, and the heating process was carried out according to  
102 the ISO 834 standard heating curve [23].

## 103 2.2 FE Model setup

104 The impact tests at room temperature were validated by the three typical columns in reference  
105 [17], and their variables were shown in Table 1. Where  $H$  is the impact height, and  $V$  is the  
106 instantaneous impact velocity of the drop hammer. The axial compression ratio  $n$  is defined as  
107  $n = N_0 / N_u$ , where  $N_0$  is the axial force of column and  $N_u$  is the nominal ultimate axial capacity

108 of CFST square column. The design strength of concrete was C40, and the average yield strength  
 109 ( $f_y$ ), ultimate strength ( $f_u$ ), elastic modulus ( $E_s$ ), and elongation ratio ( $\delta$ ) of steel with different  
 110 thickness are shown in Table 2.

111 The general-purpose software ABAQUS was used to model the impact tests column under room  
 112 temperature. The hammer head was simulated using a discrete rigid body and imposed isotropic mass  
 113 by defining reference points. Steel tube and steel profile adopt S4R elements, and concrete and  
 114 support was simulated using C3D8R elements.

115 For steel, according to the five-stage elastoplastic constitutive model of Han **Error! Reference**  
 116 **source not found.**, the stress-strain curve is shown in Eq. (1a) ~ Eq. (1e)[24]:

$$117 \quad \sigma = E_s \cdot \varepsilon \quad \varepsilon \leq \varepsilon_1 \quad (1a)$$

$$118 \quad \sigma = -A \cdot \varepsilon^2 + B \cdot \varepsilon + C \quad \varepsilon_1 \leq \varepsilon \leq \varepsilon_2 \quad (1b)$$

$$119 \quad \sigma = f_{sy} \quad \varepsilon_2 \leq \varepsilon \leq \varepsilon_3 \quad (1c)$$

$$120 \quad \sigma = f_{sy} \cdot \left[ 1 + 0.6 \cdot \frac{\varepsilon - \varepsilon_3}{\varepsilon_4 - \varepsilon_3} \right] \quad \varepsilon_3 \leq \varepsilon \leq \varepsilon_4 \quad (1d)$$

$$121 \quad \sigma = 1.6 \cdot f_{sy} \quad \varepsilon > \varepsilon_4 \quad (1e)$$

122 where,  $E_s=200,000\text{MPa}$ ,  $\varepsilon_1 = 0.8 \cdot f_{sy} / E_s$ ,  $\varepsilon_2 = 1.5 \cdot \varepsilon_1$ ,  $\varepsilon_3 = 10 \cdot \varepsilon_2$ ,  $\varepsilon_4 = 100 \cdot \varepsilon_2$ ,  $f_{sy}$  is the yieldi  
 123 ng strength of the steel. And the stress-strain curve is shown in fig. 5,  $f_{sp} = 0.8 f_{sy}$ ,

$$124 \quad f_{su} = 1.6 f_{sy}.$$

125 According to Cowper-Symonds [25] constitutive model, the strain rate effect under high  
 126 -speed motion was considered, as shown in Eq. (2):

$$127 \quad f_y^d / f_y = 1 + (\dot{\varepsilon} / D)^{1/p} \quad (2)$$

128 where  $f_y^d$  is the yield strength of steels under strain rate  $\dot{\varepsilon}$  while  $f_y$  is the yield strength of steel  
 129 rebar. Meanwhile, it was assumed that the strain rate effect does not change along with the strain

130 hardening. The values of  $D$  and  $p$  are set as  $6844 \text{ s}^{-1}$  and  $3.91$ , respectively.

131 For concrete, CDP model [26] and the constitutive model of steel tube confined concrete  
132 proposed by Han et al. [24] were adopted, the stress-strain curve is shown in Fig. 6, where the  
133 confinement factor  $\xi$  is defined as:

$$134 \quad \xi = \frac{A_s \cdot f_{sy}}{A_c \cdot f_{ck}} \quad (3)$$

135 where  $A_s$  is the cross-section area of steel tube,  $A_c$  is the cross-section area of concrete,  $f_{sy}$  is the yield  
136 stress of steel tube and  $f_{ck}$  is the compression strength of concrete. The value of  $f_{ck}$  is determined using  
137 67 % of the compression strength of cubic blocks.

138 And the strain rate effect [25] is considered, the relationship between the dynamic compressive  
139 strength of concrete and strain rate is shown in Eq. (4):

$$140 \quad f_d / f_c' = (\dot{\epsilon}_d / \dot{\epsilon}_s)^{1.026\alpha} (\dot{\epsilon}_d \leq 30 \text{ s}^{-1})$$

141 (4)

142 where  $f_d$  ( $\text{N}/\text{mm}^2$ ) is the dynamic compressive strength of concrete;  $f_c' = f_{ck} + 8(\text{N}/\text{mm}^2)$ ,  $f_{ck}$  is  
143 the characteristic static compressive strength of concrete;  $\dot{\epsilon}$  is the strain rate ( $\text{s}^{-1}$ );  $\dot{\epsilon}_s = -30 \times 10^{-6} \text{ s}^{-1}$   
144 is the static strain rate;  $\alpha = 1 / (5 + 9f_c' / f_{co})$ ;  $f_{co} = 10(\text{N}/\text{mm}^2)$ .

145 The relationship between the dynamic tensile strength of concrete and strain rate [25] is shown  
146 in Eq. (5):

$$147 \quad f_{td} / f_t = \begin{cases} (\dot{\epsilon}_d / \dot{\epsilon}_s)^\delta & \dot{\epsilon}_d \leq 1 \text{ s}^{-1} \\ \beta(\dot{\epsilon}_d / \dot{\epsilon}_s)^{1/3} & \dot{\epsilon}_d > 1 \text{ s}^{-1} \end{cases} \quad (5)$$

148 where  $f_{td}$  is the dynamic tensile strength of concrete;  $f_t$  is the static tensile strength of concrete;  
149  $\dot{\epsilon}_d$  is the strain rate ( $\text{s}^{-1}$ ) in the range of  $10^{-6}$  to  $160 \text{ s}^{-1}$ ;  $\dot{\epsilon}_s = 1 \times 10^{-6} \text{ s}^{-1}$  is the static strain rate;  
150  $\log \beta = 6\delta - 2$ ;  $\delta = 1 / (1 + 8f_c' / f_{co})$ ;  $f_{co} = 10(\text{N}/\text{mm}^2)$ .

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151 In the model, the normal direction of all contact interfaces was hard to contact, and the tangential  
152 direction was coulomb friction. The friction coefficient between concrete and steel was 0.6, and that  
153 between drop hammer and steel was 0. The end-plates were connected to the cross section by “Tie”  
154 interaction. Impact velocity was applied through predefined fields. At the same time, to facilitate  
155 subsequent data processing, the drop hammer was placed at a certain distance above the columns  
156 according to different impact velocities, so that all the columns had an impact at 0.005 s. The  
157 schematic diagram of the model is shown in Fig. 7.

158 The validation of heat transferring analysis using the results of column S3H-0.3 in reference [22].  
159 Accordance to GB5249-2017 [28] and Lie et al. [29], thermal parameters, such as thermal  
160 conductivity, specific heat and thermal expansion coefficient, and constitutive relations of steel and  
161 concrete were defined during modeling. The strain rate effect of steel and concrete under high  
162 temperature is not well studied at present, and the applications of its achievements in FE simulation  
163 are still lacking. As the degree of material degradation caused by high temperatures is more evident  
164 than that caused by strain rate, the strain rate effect parameters at room temperature are still used for  
165 steel and concrete exposed to fire. The ISO 834 fire standard heating curve [23] was adopted to  
166 uniformly heat up the three sides of the column in fire for 120 mins. The interaction of exposed  
167 surfaces includes thermal convection and radiation, and the coefficient of thermal convection and  
168 radiation are  $25 \text{ W}/(\text{m}^2 \cdot ^\circ\text{C})$  and 0.5, respectively. “Tie” was used to constrain components. Concrete  
169 adopted DC3D8 heat transfer entity, while steel tube and section steel were DS4 elements. The  
170 schematic diagram of the model is shown in Fig. 8.

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## 171 2.3 Model validation

172 Fig. 9 shows the time history curves of impact force and mid-span deflection obtained from the  
173 impact column test from [17] and simulation. As shown in Fig. 9, the simulated time history curves  
174 of impact force matched well with the test curves. The average ratio of peak impact force (FEM  
175  $F_{\max}/\text{TEST } F_{\max}$ ) was 0.9869, and the Cov. was 0.1122. The average ratio of peak mid-span  
176 deflection (FEM  $D_{\max}/\text{TEST } D_{\max}$ ) was 0.9804, and the Cov. was 0.04. Fig. 10 shows the heating time  
177 history curves at different measuring points obtained from the fire column test and simulation and the  
178 ISO 834 standard heating curve. It can be seen from the figure that the, peak temperature of heating  
179 and failure mode of the two were quite consistent.

180 Therefore, in general, the FE model in this paper can well predict the time-history curve of  
181 impact force, mid-span deflection, and internal heating curve of CSRCFST column under impact load.  
182 It can be used for coupled thermo-mechanical analysis of impact and fire action.

## 183 **3 Impact behavior of CSRCFST columns under fire**

### 184 3.1 Coupled thermo-mechanical model

185 To further explore the impact resistance of CSRCFST columns at high temperature of fire, the  
186 thermal-mechanical coupling method was used to establish the impact model under fire. Firstly, the  
187 normal temperature impact model S8HFF2 was used as the basic model, and the axial compression  
188 ratio  $n$  was kept at 0.2. Then the ODB file of the FE model for three-sided heat transfer analysis under  
189 uniform fire for 120 mins was imported into the ' predefined field ' of the basic model.

190 The constitutive relation of materials under fire was referred to the literature [27] and [30]. The

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191 interaction between steel profile and concrete was constrained by embedding while the contact model  
192 between other columns was changed to general contact. Concrete and end-plates were modelled by  
193 C3D8R elements while the steel tubes and steel profiles were modelled by S4R elements.

### 194 3.2 Impact process analysis

195 The impact force ( $F$ ), mid-span displacement ( $\Delta_1$ ), mid-span velocity ( $V_1$ ), drop weight  
196 displacement ( $\Delta_2$ ), and drop weight velocity ( $V_2$ ) during the impact testing of the column under fire  
197 were converted into normalized time-history curves, as shown in Fig. 11. The ratio of column mid-  
198 span displacement ( $\Delta_1$ ), velocity ( $V_1$ ) to the displacement ( $\Delta_2$ ) and velocity ( $V_2$ ) of the drop weight  
199 was used to obtain the time-history diagram of the ratio of displacement and velocity between the  
200 column and the drop weight, as shown in Fig. 12.

201 It can be seen from the figures that the impact history of the column under the fire was divided  
202 into four stages: the peak stage (AB), the plateau stage (BC), the softening stage (CD), and the post-  
203 impact stage (DE).

204 The peak stage is the time period from the falling weight **starting** to hit the column until the  
205 impact force reaches peaks. At this stage, the high-speed drop hammer vertically impacted the mid  
206 span of the column, and the column impact force rapidly reached the peak value within 0.0003 s. The  
207 mid span began to develop deflection, and the velocity changed and reached the peak value.  
208 Subsequently, the drop hammer and the column begin to move downward together. But the drop  
209 hammer velocity was greater than the mid-span velocity, and the energy was gradually transferred  
210 from the drop hammer to the column. At the end of the peak stage, the drop hammer velocity  
211 decreased by 17.8 %, and 32.4 % of the kinetic energy was converted into the kinetic energy and

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212 strain energy of the column.

213 The plateau stage is the period from the peak impact force to the maximum deflection of the  
214 column. At this stage, the drop hammer was still in contact with the column, and the falling velocity  
215 continued to decrease, but it was still greater than the mid-span velocity. 67.6 % of the kinetic energy  
216 continued to be converted into the kinetic energy and strain energy of the column. At the same time,  
217 the impact force dropped sharply and maintains a relatively stable value. The mid-span deflection  
218 continued to increase until reaching the maximum, and the velocity began to drop to 0 m/s. The  
219 velocity of the drop weight decreased to 0 m/s, and all the remaining kinetic energy is converted into  
220 the kinetic energy and strain energy of the column.

221 The softening stage is the period from the maximum deflection of the column until the impact  
222 force drops to 0 kN. At this stage, the drop hammer and the column began to rebound upward. All the  
223 kinetic energy of the drop hammer was consumed and transformed. The maximum deflection in the  
224 column span **was** reached. The strain energy was transformed into its own kinetic energy and the  
225 kinetic energy of the drop hammer, and the mid-span velocity was greater than the drop hammer  
226 velocity. At the same time, the column impact force decreased from a relatively stable value to 0 kN.  
227 The mid-span deflection rebound decreased, and the velocity increased inversely and then decreased  
228 to 0 m/s.

229 The post-impact stage refers to the period after the impact force drops to 0 kN. At this stage,  
230 there was no interaction between the drop hammer and the column, but the column still has a small  
231 amplitude of natural vibration, and there was residual deflection in the mid-span position.

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### 232 3.3 Comparison between room temperature and fire

233 Fig. 13 shows the comparison of the impact force versus mid-span deflection time history curve  
234 of the column under room temperature and fire. It can be seen from the figure that there was a great  
235 difference between the impact dynamic response of the column under these two conditions. The  
236 impact stiffness of the column under room temperature and fire was 119.2 kN/mm and 7.5 kN/mm,  
237 respectively. The impact stiffness of column under fire decreased by 93.7 %. The peak impact force  
238 under room temperature and fire was 23.9 kN and 6.8 kN, respectively. The peak impact force under  
239 fire decreased by 71.71 %. The maximum mid-span deflection of the column under fire and room  
240 temperature was 23.0 mm and 21.6 mm, respectively. The maximum mid-span deflection of the  
241 columns under fire increased by 6.50 %. The residual deflections of columns under fire and room  
242 temperature were 18.5 mm and 15.4 mm, respectively. Thus, the residual deflections of columns  
243 under fire increased by 20.1 %. The comparison shows that under high temperature of fire, the column  
244 material performance deteriorates, the overall strength decreases, the stiffness weakens, and the mid-  
245 span deflection and residual deflection generated by impact are larger.

### 246 3.4 Axial force and support reaction force

247 Fig. 14 shows the time-history curves of axial force and support reaction force (excluded column  
248 gravity) in the process of column impact under fire. It can be seen from the figure that at the peak  
249 stage, axial force and support reaction force increased rapidly. When the axial force reached the peak  
250 value of 895.6 kN, the unloading began, and the support reaction increased to 367.1 kN. This was  
251 because at the moment of impact, the shock wave spread from the mid-span area along the column to  
252 both sides of the support, squeezing the spring and increasing the axial force. Then, due to the

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253 continuous deformation of the column, the horizontal distance of the beam end decreased, so that the  
254 spring was extruded to **elongate**, and the axial force began to unload and increased in reverse. At the  
255 same time, the column was subjected to the impact force of the falling hammer, resulting **in** upward  
256 reaction force. In the plateau stage, the axial force continued to increase to the peak value of 746.9  
257 kN and then vibrated. The support reaction continued to increase to a peak of 5367.1 kN. This was  
258 due to a large deflection of the column at this stage, and the continuous decrease of horizontal distance  
259 at the beam end weakened the influence of shock wave on the axial force, and the axial force increased  
260 to the peak value and fluctuates. At the same time, the drop hammer was still moving downward,  
261 continuing to produce a downward force on the column. In the descending stage, the axial force began  
262 to increase again, and the support reaction force rapidly offloaded and increased in reverse. This was  
263 because at this stage, the column began to rebound, the horizontal distance of the beam end increased,  
264 and gradually approached the initial length, so that the axial force increased again. At the same time,  
265 the drop hammer also began to rebound, no longer **producing** downward impact force on the column,  
266 so that the support reaction force was quickly unloaded. When the column bounces back to the initial  
267 state, it would still move upward due to inertia, making the reaction force of the support increase in  
268 reverse. In the post-impact stage, the axial force and support reaction force both oscillated at a certain  
269 value due to the existence of the natural vibration of the column.

### 270 3.5 Strain distribution

271 Fig. 15 shows the distribution of equivalent plastic strain of the steel tube and concrete. As  
272 shown in Fig. 15, the plastic strain of the steel tube was mainly concentrated in the impact zone and  
273 extending to the support on both sides, and a "drum-like" plastic concentration zone was formed in

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274 the middle of the cable-stayed zone. This was because the column height was large resulted in  
275 relatively large shear span ratio. However, the impact energy was large and its action time was short.  
276 The weak stress in the middle of the cable-stayed area developed rapidly and diffused around, forming  
277 a “Plastic Drum”. The plastic strain of steel profiles was low and mainly concentrated in the area  
278 between the middle span and the support. The maximum plastic strain of concrete mainly  
279 concentrated in the middle span, and extended to both sides of the support as a stripy-like area. The  
280 results show that the deformation modes of steel tube, concrete, and steel profiles were relatively  
281 consistent, and they bear the impact load together. Among them, the steel tube has a large strain and  
282 high energy consumption, which can protect the core concrete during impact. At the same time, the  
283 internal cross steel profiles can enhance the stiffness of the column and effectively reduce the concrete  
284 strain.

## 285 **4 Parametric analyses**

### 286 4.1 Mass of drop hammer

287 **Figs. 16 and 17** show the impact force time history curve and deflection time history curve of  
288 the column under a different mass of drop hammer impact. The mass of drop hammers M1 to M4  
289 were 579.4 kg, 1158.7 kg, 1738.1 kg, and 2317.4 kg, respectively. It can be seen from the figure that  
290 with the increase of drop hammer mass, the peak impact force of column did not increase significantly.  
291 From M1 to M4, when the drop hammer mass increased by 3 times, the peak impact force only  
292 increased by 14.5 %, this is because the contact stiffness between the drop hammer and the column  
293 is almost unchanged. By contrast, the impact force at the plateau stage increased considerably, from  
294 about 1.7 MN to 2.9 MN, an increase of 70.6 %. This is because the interaction between the drop

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295 hammer and the column enhanced with the increase of inertial force, which increased the impact force  
296 and impact time at the plateau stage. At the same time, the maximum deflection and residual  
297 deflection of the column were increased. The maximum deflection and residual deflection of M4  
298 column are 2.8 and 3.2 times of those of M1 column, respectively. The moment when the column  
299 reaches the maximum deflection increases from 0.0075 s to 0.0130 s. This is due to the greater  
300 interaction force and longer interaction time between the heavy drop hammer and the column.

#### 301 4.2 Impact momentum

302 Impact energy is an important factor affecting the impact process of column. However, when the  
303 impact energy is the same and the impact momentum is different, the dynamic response produced by  
304 the column is also different. Therefore, the drop weight mass and impact velocity are adjusted at the  
305 same time to ensure that the energy of each impact is the same but the momentum is different, and  
306 the impact dynamic response of the column is studied. Table 3 lists the variable parameters for the  
307 different columns.

308 Figs. 18 and 19 show the impact force time history curve and mid-span deflection time history  
309 curve of the column under fire in the same impact energy but different momentum. It can be seen that  
310 the impact dynamic response of the column under different momentum shows great difference. The  
311 larger the momentum is, the smaller the peak impact force is, and the larger the impact value is in the  
312 plateau stage. When the impact momentum was doubled, the peak impact force decreased by 35.2 %.  
313 This was because under the premise of the same impact energy, when the momentum increased, the  
314 impact velocity of the drop hammer would decrease, and the action time when contacting the column  
315 increased. According to the momentum theorem:  $\Delta p = F \Delta t$  ( $\Delta p$  represents the change of momentum,

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316  $F$  represents the impact force, and  $\Delta t$  represents the change of action time), the impact force  
317 generated by the column would be reduced. At the same time, under the premise of the same impact  
318 energy, the column drop hammer with larger momentum had larger mass, larger inertia force, and  
319 stronger continuous impact on the column, making the impact value of the column plateau stage larger,  
320 increased by 27 % from about 2.2 MN to 2.8 MN. It is worth noting that the maximum deflection and  
321 residual deflection of all columns were almost the same. This was because the energy of impact was  
322 the same, and the energy of deformation converted into the column was the same, which conformed  
323 to the energy conservation law.

#### 324 4.3 Fire duration

325 Figs. 20 and 21 show the time history curves of impact force and mid-span deflection under  
326 different fire durations. FT-1h, FT-2h, and FT-3h represent specimens with fire durations of 1 hour, 2  
327 hours, and 3 hours, respectively. From the figure, it is evident that the fire duration greatly influences  
328 the impact resistance of the specimens. The peak impact force decreased by 85 % from 17.7 MN to  
329 2.6 MN when the fire duration increased from 1 hour to 3 hours. The maximum mid-span deflection  
330 increased by 39 % from 18.3 mm to 25.4 mm. The impact time increased from 0.0066 seconds to  
331 0.0112 seconds at the same time. As a result of effects of high temperature, the specimen material  
332 gradually deteriorates, and the contact stiffness between the drop hammer and the specimen is greatly  
333 reduced when the impact happens, resulting in a greater reduction in peak impact force. Additionally,  
334 the decrease in stiffness of the specimen weakens the impact resistance, so that the maximum mid-  
335 span deflection increases, and the impact time is prolonged as a result of the longer contact time  
336 between the softened specimen and the drop hammer.

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#### 337 4.4 Impact velocity

338 Previous impact tests in the room temperature had indicated that the height or velocity of the  
339 impact has great effects on the impact response of the specimens. To assess the effects of impact  
340 velocity on the impact behavior of CSRCFST columns under fire, a series of FE models were built.  
341 Figs. 22 and 23 show the time history curves of impact force and mid-span deflections. V1, V2, V3  
342 and V4 in the figures represent the specimens with impact velocities of 5.42 m/s, 7.67 m/s, 9.39 m/s  
343 and 10.84 m/s respectively. It can be seen from the figures that the impact velocity has a great  
344 influence on the peak impact force, the impact force of plateau stage, the mid-span deflection and the  
345 impact duration of the specimen. When the impact velocity increases from 5.42 m/s to 10.84 m/s, the  
346 peak impact force increases from 4.3 MN to 8.4 MN, increasing by 95 %. The impact force of plateau  
347 stage increases slightly, but the duration of the plateau stage increases significantly. At the same time,  
348 the maximum mid-span deflection of the specimen increased from 10.7 mm to 28.6 mm, an increase  
349 of 167 %. This is because the larger the impact velocity represents greater momentum but shorter  
350 initial contact time between the drop hammer and the specimen when the impact mass kept unchanged.  
351 According to the momentum theorem:  $\Delta p = F \Delta t$ , when  $\Delta p$  increases and  $\Delta t$  decreases,  $F$  will  
352 be larger. At the same time, greater impact velocity is accompanied by greater impact energy, which  
353 is converted into more strain energy of the specimen, and the conversion time is longer.

#### 354 5 Conclusion

355 In this paper, the FE numerical simulation was carried out to quantify the impact response of  
356 CSRCFST column under room temperature and fire. The model was validated and calibrated using  
357 existing tests. Using the validated FE model, the impact dynamic response of the column under fire

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358 was studied, and the parameters such as drop weight, impact momentum, fire duration, and impact  
359 velocity were analyzed. The following conclusions are drawn:

360 1. The numerical results of the impact test under room temperature and the fire are both in good  
361 agreement with the experimental results, and the established model is reasonable and effective.

362 2. The impact process of CSRCFST columns under fire can be divided into peak stage, plateau stage,  
363 descending stage, and post-impact stage. The peak stage and the plateau stage are the main impact  
364 stages. The kinetic energy is obviously transformed, consuming 32.4 % and 67.6 % of impact  
365 kinetic energy, respectively. The axial force and support reaction force response are also the  
366 largest, with peak values of 1895.6 kN and 5367.1 kN in the peak stage and plateau stage  
367 respectively.

368 3. Steel tube, concrete, and steel profile worked together to resist impact under fire. The steel tube  
369 has a large strain and a lot of energy consumption. The internal cross steel profile can enhance the  
370 column stiffness, which can protect the core concrete and reduce the strain.

371 4. The mass of drop weight is an important factor affecting the impact performance of CSRCFST  
372 columns under fire, and the impact on deflection is greater than impact force. When the mass of  
373 drop weight increases by 3 times, the maximum mid-span deflection and residual deformation  
374 increase by 2.8 and 3.2 times respectively, and the impact force at the plateau stage increase by  
375 70.6 %, but the peak impact force only increases by 14.5 %.

376 5. When the impact kinetic energy is constant, the impact momentum is negatively correlated with  
377 the peak impact force of the column. When the impact momentum is doubled, the peak impact  
378 force decreases by 35.18 %. The maximum deflection and residual deflection in the column span  
379 are consistent with the impact energy.

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380 6. The increase of fire duration will seriously deteriorate the impact performance of CSR CFST  
381 columns, which will greatly reduce the peak impact force and increase the mid-span deflection;  
382 The change of impact velocity has an influence on the whole impact process of CSR CFST column,  
383 and is positively related to the peak impact force, platform stage impact force and mid-span  
384 deflection.

385 7. Overall, CSRCFST columns have good impact resistance under fire. Therefore, in the test or  
386 practical engineering design, it can be considered to add cross steel profile to CFST columns to  
387 enhance the fire resistance and impact resistance of the columns.

### 388 **Acknowledgements**

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**Table 1-** Typical column variable parameters of room temperature impact field

Specimen label	$H$ (m)	$V$ (m/s)	$n$
S8MFF0	3.0	7.67	0.0
S8HFF1	4.5	9.39	0.1
S8HFF2	4.5	9.39	0.2

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**Table 2-** Steel properties

$t$ (mm)	$f_y$ (MPa)	$f_u$ (MPa)	$E_s$ (MPa)	$\delta$ (%)
6	427.0	625.3	$2.10 \times 10^5$	22.2
8	400.6	564.0	$2.06 \times 10^5$	21.3
9	358.2	529.4	$2.03 \times 10^5$	23.0

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**Table 3-** Specimen properties

Specimen label	Drop hammer quality (kg)	Impact velocity (m/s)	Impact energy (kJ)	Impact momentum (kg·m/s)
E-P1	869.4	10.84	51.1	9424.3
E-P2	1158.7	9.39	51.1	10880.2
E-P3	1736.6	7.67	51.1	13319.8
E-P4	3477.8	5.42	51.1	18849.7

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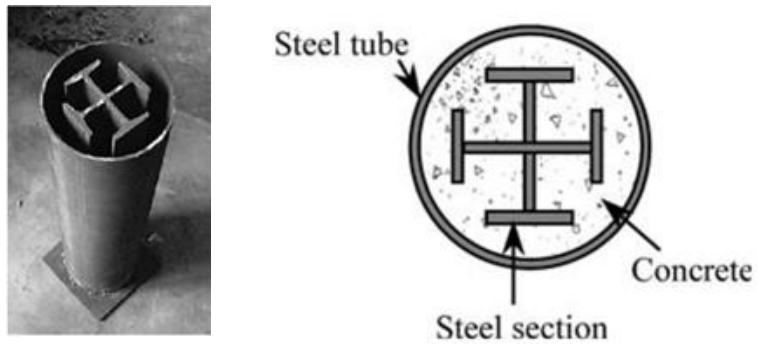
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**Figure. 1.** New CSRCFST structure from [11]

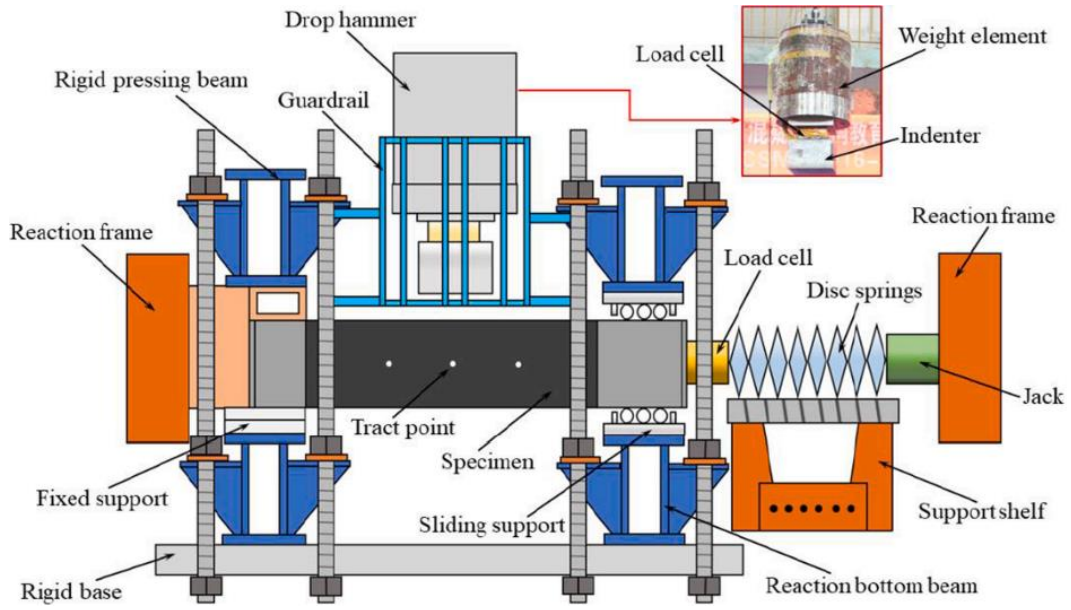


Figure. 2. Room temperature impact test device in [17]

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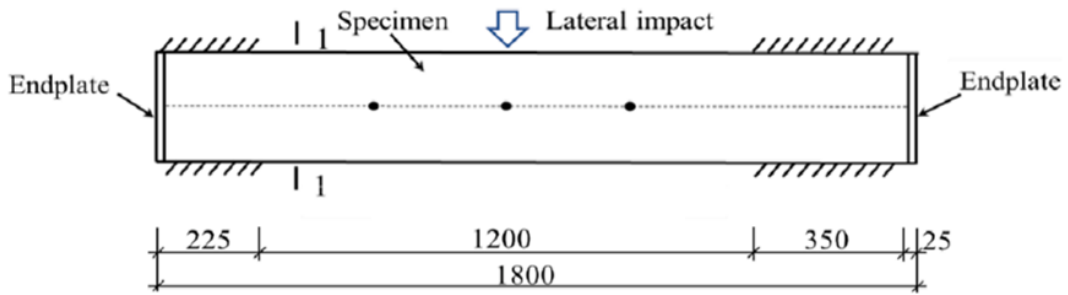
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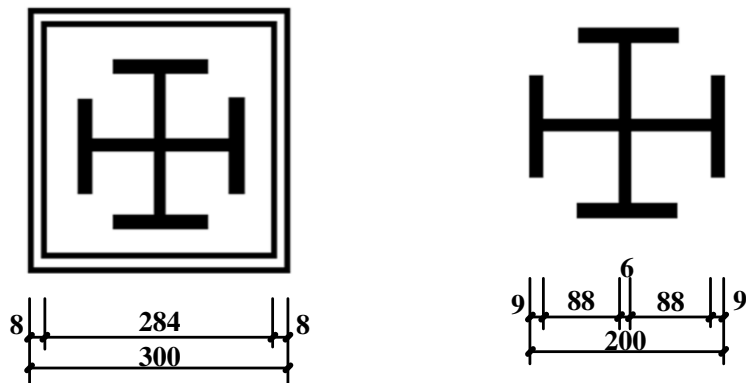
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(a)



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(b)

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**Figure. 3.** CSRCFST column details and section dimension [17]: (a) column details; (b)

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column section dimension

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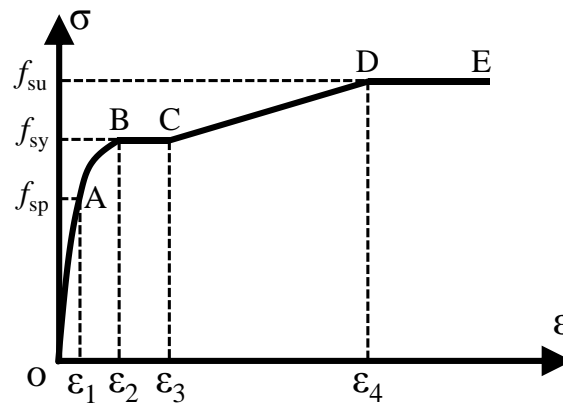


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**Figure. 4.** Fire test device in [22]

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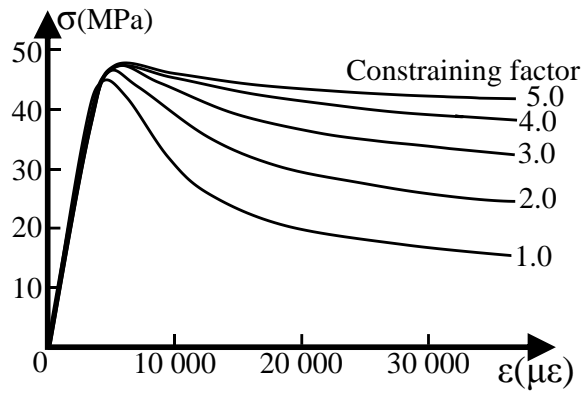


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**Figure. 5.** Stress-strain curve of the steel [24]

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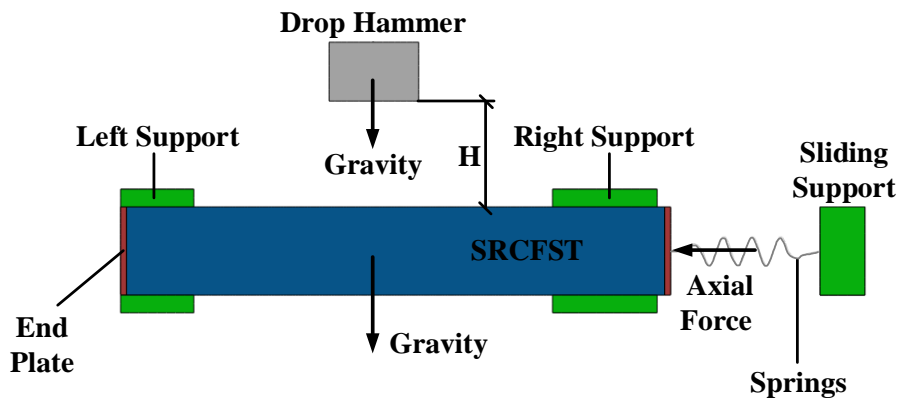


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**Figure. 6.** Stress-strain curves of concrete in different constraining factors [24]

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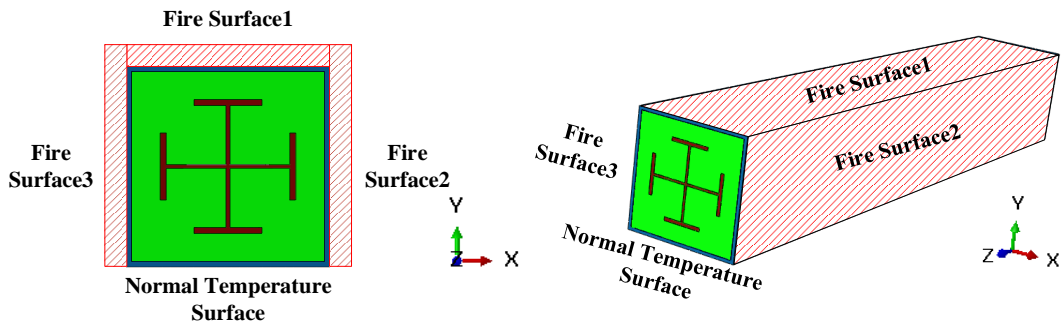
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**Figure. 7.** Model for impact test under room temperature

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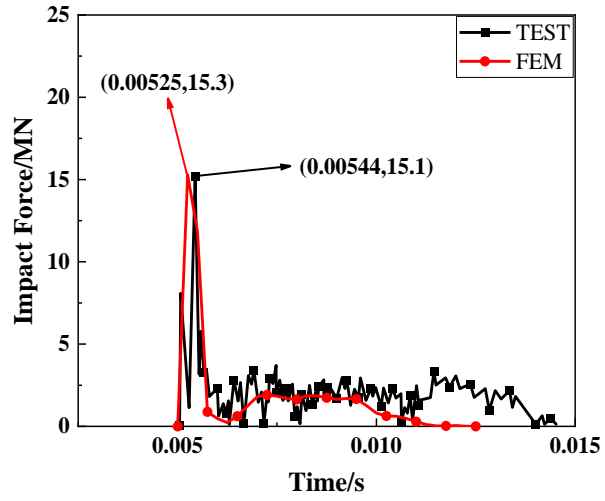


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**Figure. 8.** Heat transferring analysis model

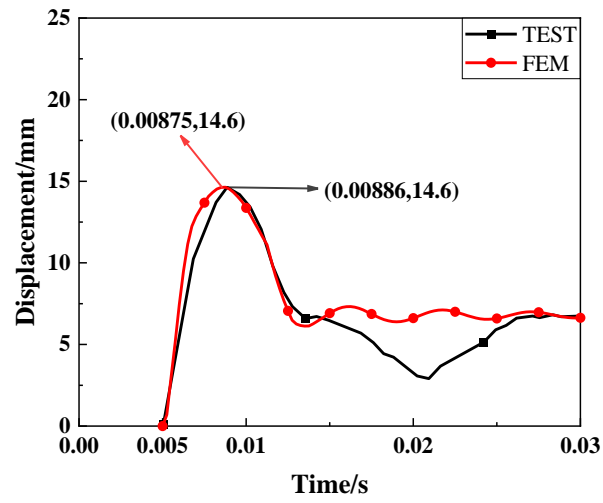
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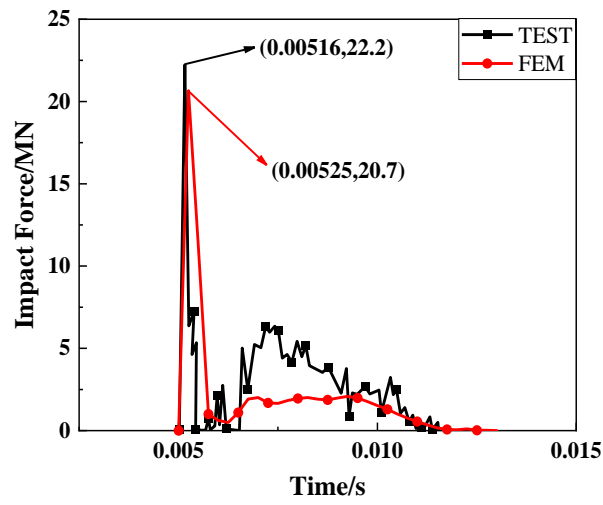
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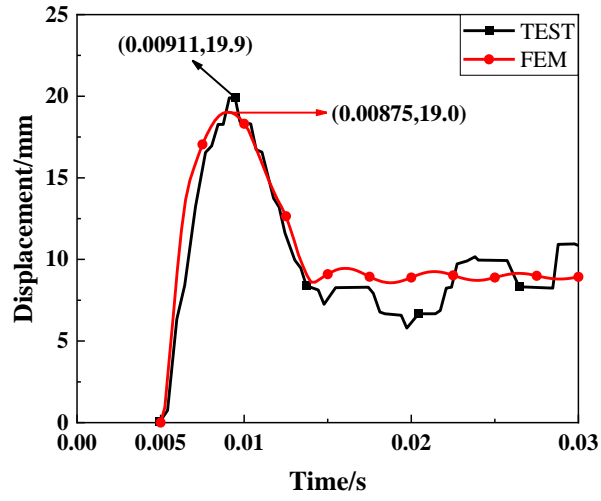
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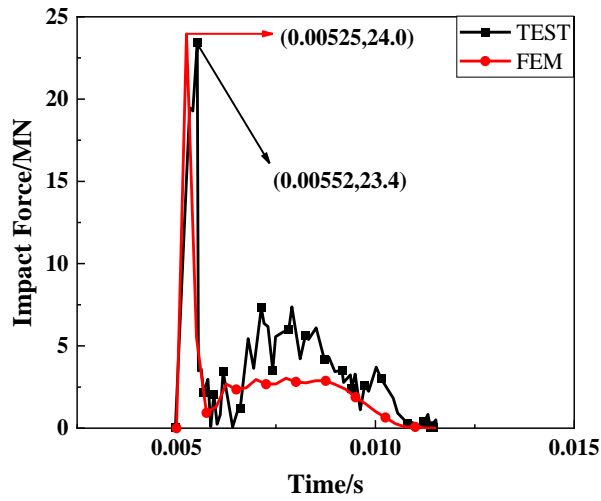
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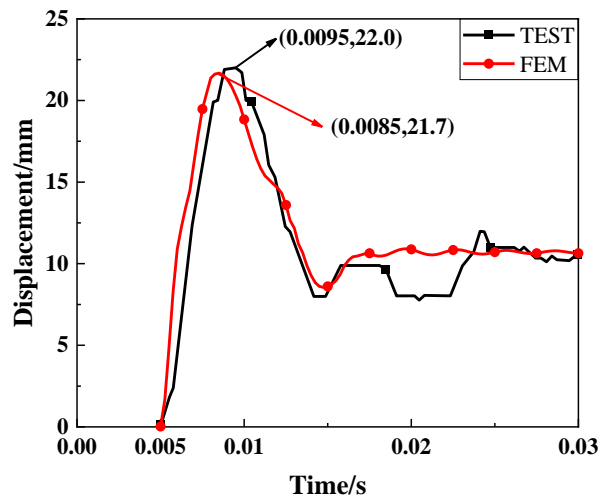
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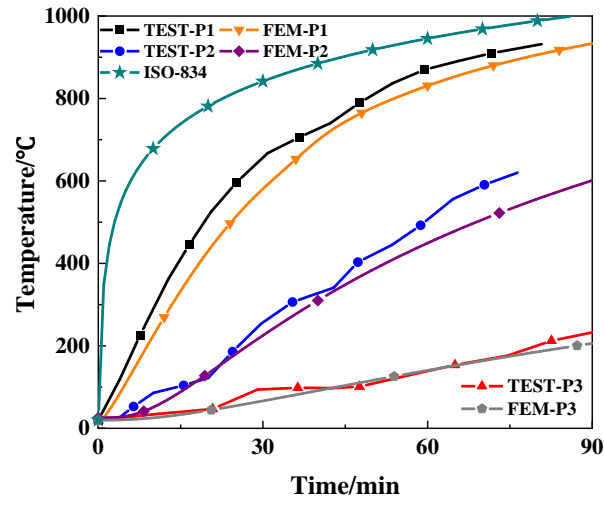
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**Figure. 9.** Comparison of time history curves of impact force and mid-span deflection of impact columns: (a) S8MFF0; (b) S8MFF0; (c) S8HFF1; (d) S8HFF1; (e) S8HFF2; and (f) S8HFF2

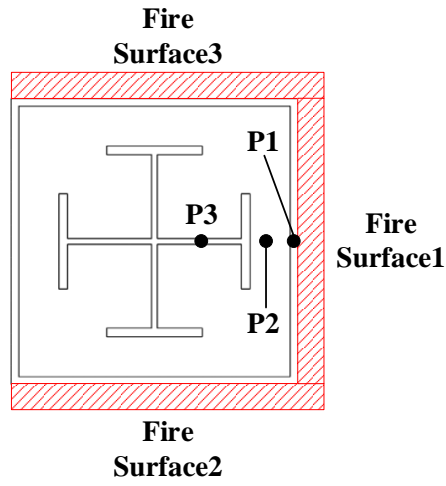
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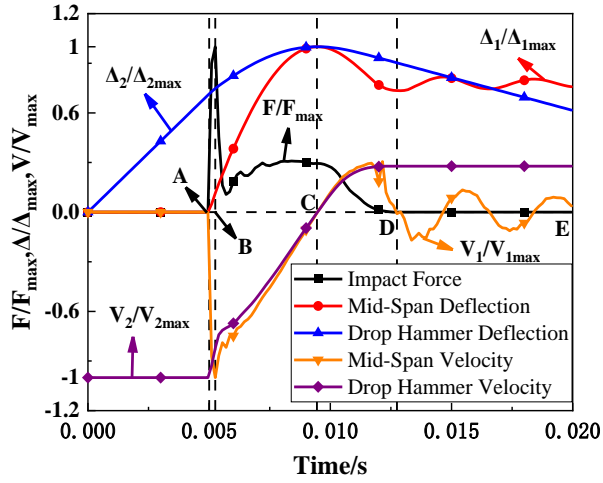
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(b)

581 **Figure. 10.** Time temperature curves at different measuring points of fire components: (a)

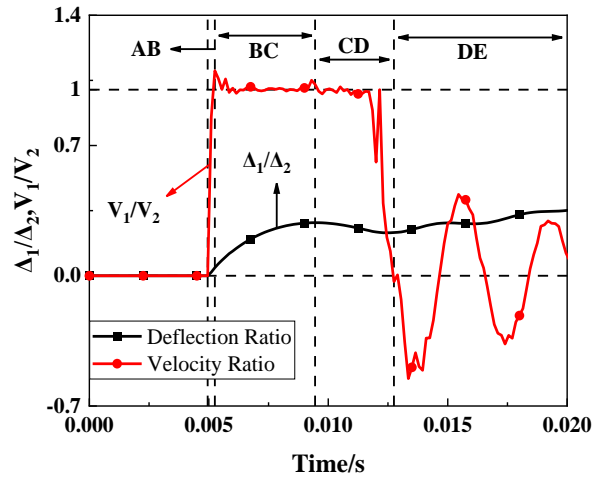
582 temperature rise time history curve; (b) temperature measuring point location

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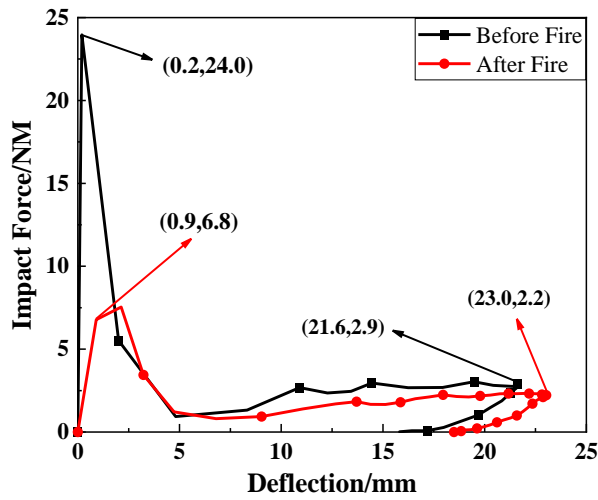
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Figure. 11. Dimensionless time history curve



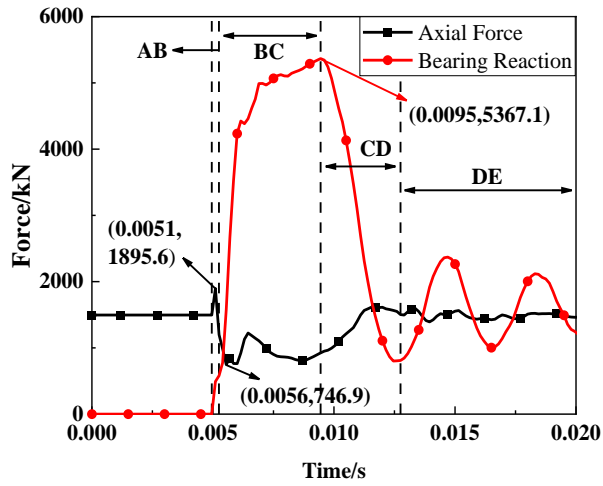
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Figure. 12. Time history curve of displacement velocity ratio



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Figure. 13. Time history curve of impact force - mid-span deflection

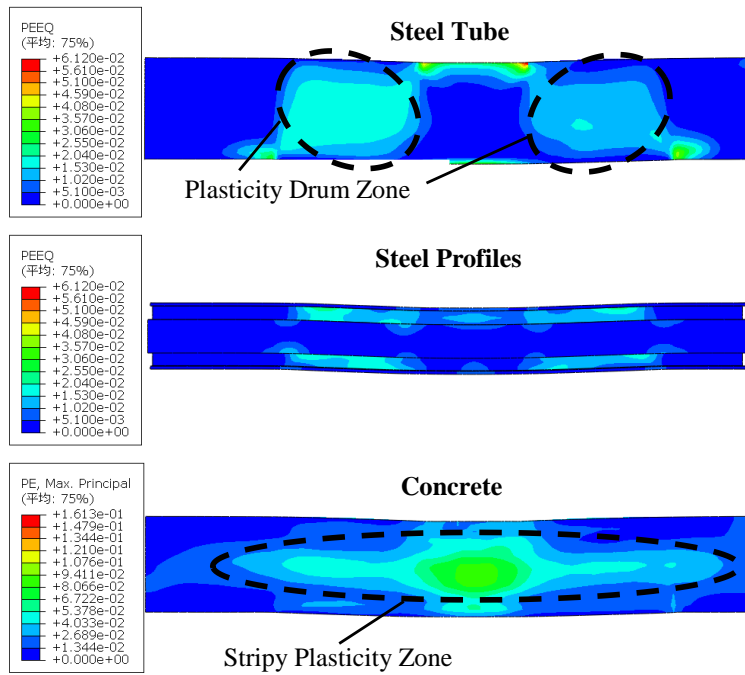


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**Figure. 14.** Time history curve of axial force and support reaction force

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**Figure. 15.** Strain nephogram

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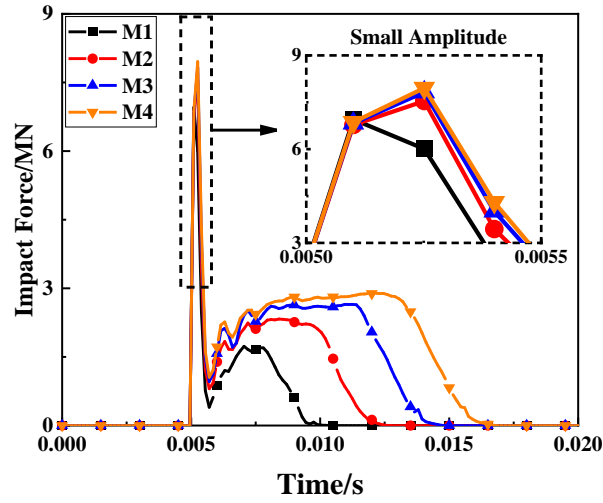


Figure. 16. Time history curve of impact force

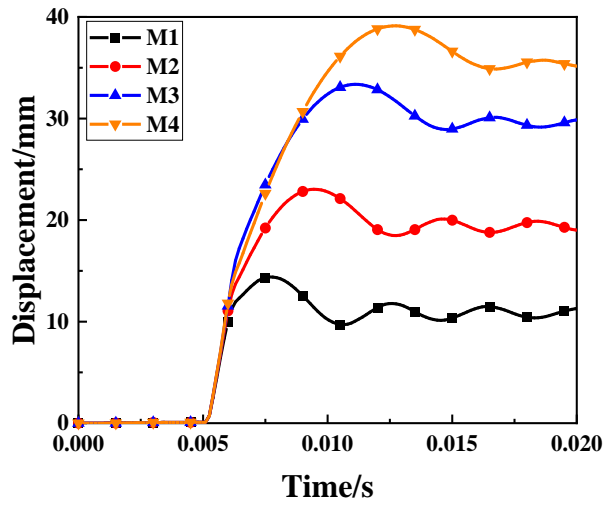


Figure. 17. Time history curve of mid-span deflection

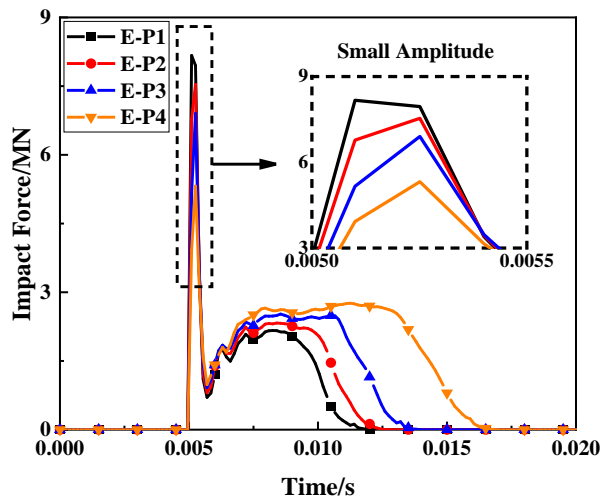
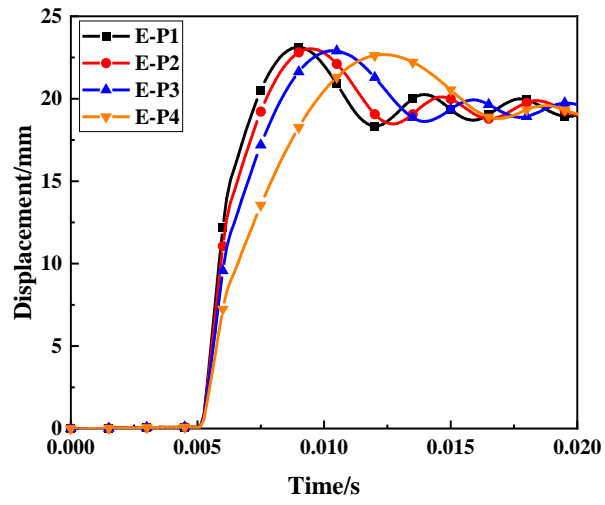


Figure. 18. Time history curve of impact force

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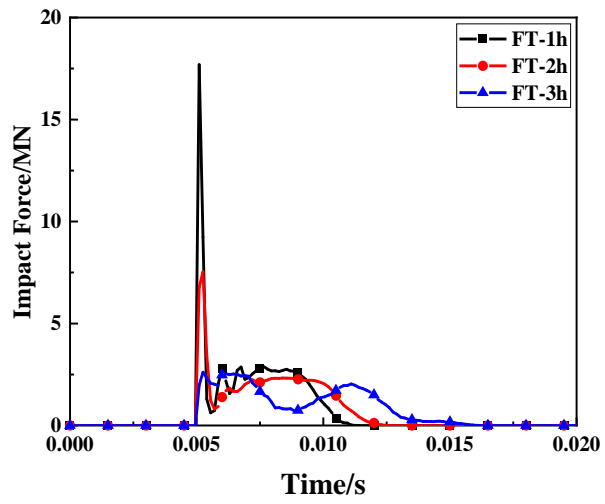


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Figure. 19. Time history curve of mid-span deflection

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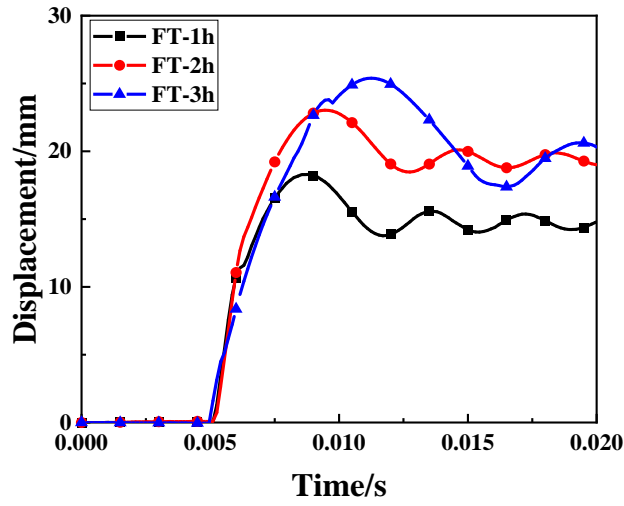


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Figure. 20. Time history curve of impact force

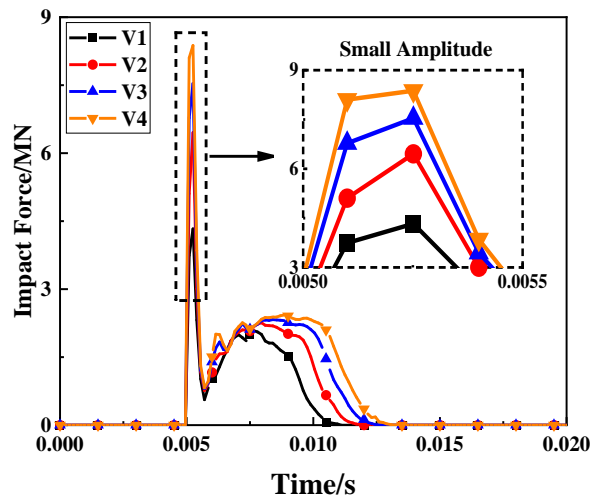
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Figure. 21. Time history curve of mid-span deflection

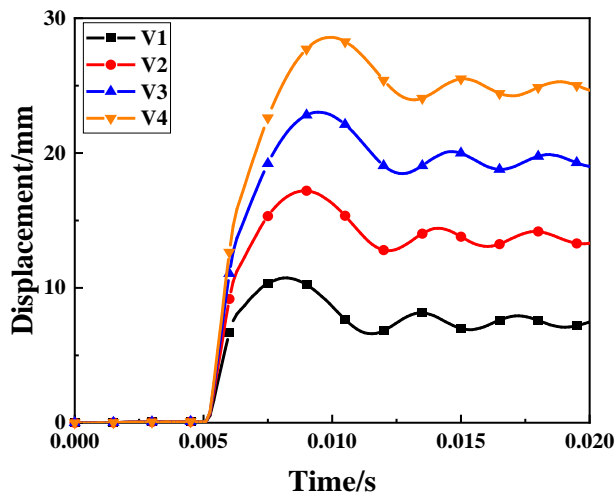


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Figure. 22. Time history curve of impact force



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Figure. 23. Time history curve of mid-span deflection