International Journal of Steel Structures (2022) 22(6):1918–1929
https://doi.org/10.1007/s13296-022-00686-z

Online ISSN 2093-6311
Print ISSN 1598-2351

Post-fire Study on Mechanical Properties of Damaged Ultra-high Strength Concrete

Xiao Lyu[1,2] · Guang-Hao Jia[1,2] · Gan-Ping Shu[3,4] · Xin Zhang[1,2] · Er-Feng Du[3,4] · Wen-Ming Wang[1,2]

Received: 30 December 2021 / Accepted: 14 October 2022 / Published online: 31 October 2022

Abstract

In order to study the effect of steel tube, pre-load and temperature on residual performance of heated ultra-high strength concrete (UHSC), an experimental program was carried out to investigate the physical and mechanical properties of UHSC post-fire in room temperature. With total of 54 standard cylindrical concrete specimens subjected to various temperatures ranging from 62 °C to 496 °C, their residual compressive strength, elastic modulus, peak strain was measured after natural cooling down. By comparing the test results of standard cylindrical concrete specimens with the results of the bare specimens in and after fire, it is known that the residual compressive strength of standard cylindrical concrete specimens decayed more serious after exposing to same temperature. Seen from the results, the temperature which the specimens suffered was found to be responsibility to the reduction of the compressive strength, elastic modulus, peak strain. As the temperature up to 300 °C, the strength reduction coefficient of UHSC was 0.67 ~ 0.68 and the elastic modulus reduction coefficient of UHSC was 0.41 ~ 0.51 with peak strain coefficient $\varepsilon_{cr}(T)/\varepsilon_0$ 1.57 ~ 1.67. Finally, based on the analysis of test results, simple formulae were proposed to describe the effect of temperature on residual performance of heated UHSC which infilled the steel tube.

Keywords Ultra-high strength concrete · Steel tube · Physical and mechanical properties · Post-fire · Experiment

1 Introduction

Nowadays, with the growth of engineering structure towards large span, high rise and even ultra-high rise, the applications of Ultra-high strength concrete (UHSC) filled steel tubular columns were increasing. UHSC had been found to be attractive alternatives to normal strength materials for high-rise construction. One of the significant uses of UHSC in high-rise buildings is for concrete filled steel tubular (CFST) columns. The columns constitute the main load bearing components in a building and hence, the provision of appropriate fire safety measures is one of the main safety requirements in high-rise building design. It was because the composite column had many advantages in load-bearing, for example, the steel casing confines the concrete laterally, allowing it to develop its optimum compressive strength, while the concrete, in turn, prevented elastic local buckling in the steel wall (Lyu et al., 2018; Xiong et al., 2017; Romero et al., 2015; Wang et al., 2022a, 2022b). The uses of UHSC can reduce member sizes and payload acting on foundation, which will require less construction materials and handling works. The combination of UHSC and steel to form concrete-filled steel tubular (CFST) columns

✉ Xiao Lyu
xiaolv_seu@126.com

Guang-Hao Jia
1345155821@qq.com

Gan-Ping Shu
sgp0818@vip.sina.com

Xin Zhang
zhangxin@sdjzu.edu.cn

Er-Feng Du
erfengdu@163.com

Wen-Ming Wang
13743@sdjzu.edu.cn

1 School of Civil Engineering, Shandong Jianzhu University, Jinan 250101, China

2 Key Laboratory of Building Structural Retrofitting and Underground Space Engineering (Shandong Jianzhu University), Ministry of Education, Jinan 250101, China

3 School of Civil Engineering, Southeast University, Nanjing 211189, China

4 Key Laboratory of C and PC Structures (Southeast University), Ministry of Education, Nanjing 211189, China

is more attractive compared with the columns employing either UHSC or steel due to enhanced strength and stiffness (Song & Xiang, 2020; Lyu et al., 2020; Karimi et al., 2020; Xu et al., 2022a, 2022b). Another advantage of concrete filling was that it also increased the fire resistance of the column without the need for external fire protection for the steel (Kodur, 1998). This increased the usable space in the building. In recent years, ultra-high strength concrete has become an attractive alternative to traditional plain concrete, since it further increased the load-carrying capacity of steel hollow structural section columns (Huang et al., 2021; Liu et al., 2021). When concrete structures were exposed to fire temperatures, it was easily affected by high temperatures in the event of fire, their internal structure would change, and then the service life of the structure could decrease due to the deterioration of its strength and deformation capacity (Xu et al., 2022; Cai et al., 2021; Kim et al., 2016). As the main component of the composite column, UHSC in room temperature and in high temperature was studied by many researchers (Du et al., 2020; Lee et al., 2020; Liew et al., 2014; Chung et al., 2013; Wang et al., 2022a, 2022b; Li et al., 2018). The elastic modulus was less affected by the temperature in HSC compared with NSC according to the literature (Bamonte & Gambarova, 2010). Generally, steel fibers increased both the compressive strength and elastic modulus (Aslani & Samali, 2013a, 2013b), whereas polypropylene fibers decreased the compressive strength but increase the elastic modulus (Aslani & Samali, 2013a, 2013b). There was little available in the literature on its performance post-fire. In this paper, test results of mechanical properties of ultra-high strength concrete post-fire in room temperature were presented.

Modifications to the mineralogy and the micro-structure of the material were generated after heating to high temperatures, with chemical and physical transformations in aggregates and cement paste with a possible increase of small pores and micro-cracks within the concrete inside the tube. To evaluate the residual capacity of structural members with the UHSC, the knowledge of the temperature-dependent mechanical properties post-fire, such as compressive strength and modulus of elasticity, was required. In the earlier work, fire resistance experiment of ultra-high strength concrete (UHSC) filled steel tubular (including circular tube and square tube) columns was conducted (Xiong & Liew, 2021), shown in Fig. 1. In order to study the effect of steel tube, pre-load and temperature on residual performance of heated UHSC, an experimental program was carried out to investigate the physical and mechanical properties of ultra-high strength concrete post-fire in room temperature. The long composite columns were cut into small pieces and the UHSC was got out from the part of ultra-high strength concrete filled steel tube columns and made into standard cylindrical specimens after exposure to different temperatures. 3 standard cylindrical specimens were in 1 group and there were 18 groups of the test specimens. 10 groups were got out from UHSC filled circular tube columns and the others were got out from UHSC filled square tube columns. With total of 54 standard cylindrical concrete specimens subjecting to various temperatures ranging from 62 °C to 496 °C, their residual compressive strength, elastic modulus was measured after natural cooling down. Seen from

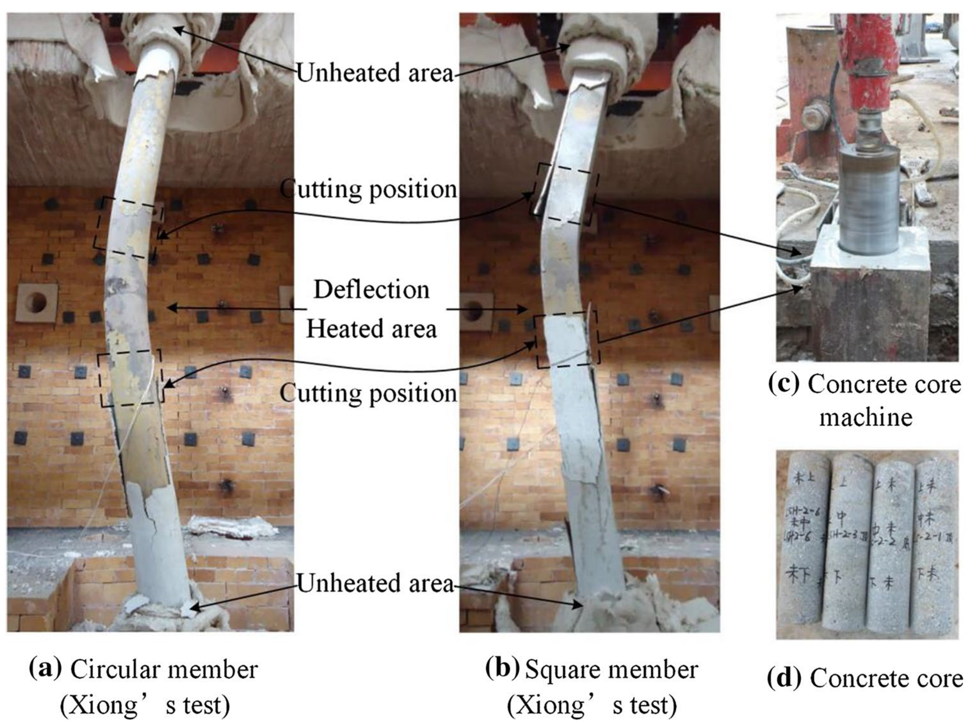


Fig. 1 Fire resistance of long members

the results, the temperature which the specimens suffered was found to be responsibility to the reduction of the compressive strength and elastic modulus and so on. In other words, the temperature played an important role and led to a big degradation in UHSC mechanical properties.

2 Test Program

2.1 Specimens Making

The basic materials of UHSC were made from a pre-blended mixture comprising cementitious material superplasticizer, cementitious mineral powder and fine aggregates with maximum sizes less than 4.75 mm, 49% < 0.6 mm, which was called D4, as one of the commercial Ducorit® products. (Xiong & Liew, 2016). The slump flow spread was 735 mm. Workability of the fresh UHSC was tested using the slump flow test in accordance with ASTM C1611/C1611M-09b. The mixing proportions for the UHSC were shown in Table 1. The UHSC was got out from the part of ultra-high strength concrete filled steel tubular (including circular tube and square tube) columns and made into standard cylindrical specimens. For the standard compression tests, cylinder specimens with a nominal height of 100 mm and a diameter of 100 mm were prepared. The actual diameters and heights were measured before the test started. A strain gauged sensor with length of 50 mm was attached to the middle 1/2 height of the specimen. With total of 54 standard cylindrical concrete specimens subjected to various temperatures ranging from 62 °C to 496 °C, their residual compressive strength was measured after natural cooling down.

Generally, the microstructure of concrete after experiencing the fire temperature of 100 °C has little change compared with that at room temperature, which is conducive to the hydration of cement and accelerate the growth of hydration compounds. After the concrete experiences the fire temperature of 300 °C, the crystalliferous water in the concrete begins to disperse and the hydrates begin to decompose. After experiencing the fire temperature up to 500℃, concrete crystal water almost all lost, cement hydrate decomposition almost exhausted, aggregate phase also began to dehydrate, and concrete surface appeared obvious cracks. All the cylinder specimens taken out from the composite columns were shown in Fig. 2.

Table 1 The mixing proportions of UHSC

Water/D4	Water (kg)	D4 (kg)	UHSC volume (m^3)
0.076	101.1	1329.8	0.5

Fig. 2 Standard cylinder specimens

2.2 Test Procedure

The cylinder specimens taken out from composite columns were processed to be standard cylinder specimens following Chinese standard CECS 03:2007 (CECS, 2007). The compression tests were conducted by means of a servo-hydraulic testing machine with capacity of 2,000 kN and a maximum 200 mm stroke displacement. Due to the high compressive strength of concrete before the fire, greater than 60 MPa, the test loading speed was set as 3.9 kN/s (ASTM C 469-02, 2002). When the specimen was close to failure (80–85% of estimated bearing capacity of each specimen) and began to rapidly deform, the throttle of the testing machine was slowed down (loading speed 1.5 kN/s) and adjusted until the specimen was destroyed, and the failure load was recorded. Considering the high compressive strength of concrete core sample, transparent soft glass was used as the anti-collapse net, and the observation of experimental phenomenon in the loading process was carried out.

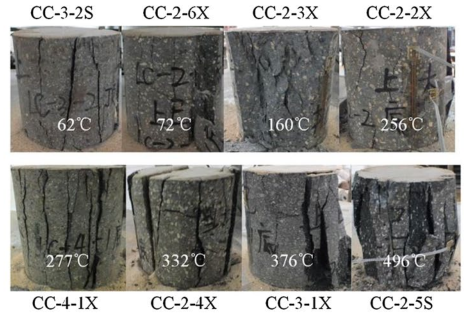
After uniaxial compression test, the failure of high strength concrete core was mainly vertical splitting, with obvious vertical through-crack and "flake" concrete falling off the outer surface of specimen. Some specimens were even broken with circular cracks at the end. This was because under a certain load level, the core concrete in the steel pipe has been irreparable damage under the combined action of load and high temperature. The internal micro-cracks and concrete reaction under high temperature make the mechanical properties of concrete itself worse. Besides, there were more obvious brittleness characteristics. After being subjected to high temperature, the compound inside concrete lost crystal water, and the carbonation inside the core of high-strength concrete is more obvious, showing a darker black color. The standard specimens were obtained from the central position of core concrete. Therefore, the temperature experienced by the concrete core sample after fire is the average of the two measuring points, points 1 and 2. Three thermocouples were set on the composite column, as shown in Fig. 3a and b. The damage of the specimens with different temperature after cooling down and test was shown in Fig. 4a–c.

3 Results and Discussion

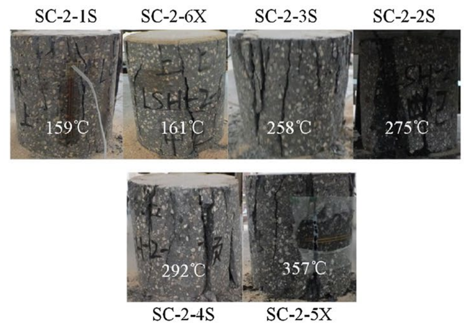
3.1 Mechanical Properties

The residual strength $f_{cr}(T)$, residual elastic modulus $E_{cr}(T)$ and peak strain $\varepsilon_{cr}(T)$ of UHSC after fire are obtained according to the test. Due to the limitation of test conditions and the number of concrete core samples, the secant modulus corresponding to $0.4f_{cr}(T)$ was adopted in this paper to determine the residual elastic modulus $E_{cr}(T)$ of UHSC after fire. In order to study the strength reduction of UHSC in steel tubes after fire and assess the effect of temperatures on the concrete mechanical properties, the ratio of residual strength of UHSC after fire to compressive strength at room temperature, $f_{cr}(T)/f_c$, was defined as compressive strength reduction coefficient. $E_{cr}(T)/E_c$ and $\varepsilon_{cr}(T)/\varepsilon_0$ were defined as reduction coefficient of elastic modulus and peak strain coefficient, respectively. The results of these comparisons were shown in Tables 2, 3, 4, 5, 6, 7.

Seen from Tables 2, 3, 4, 5, the compressive strength and elastic modulus of UHSC decreased obviously with the high temperature the specimens suffered, while the peak strain of UHSC rose as the temperature went up, shown in Tables 6 and 7.



(a) Failure mode of specimens from circular composite columns

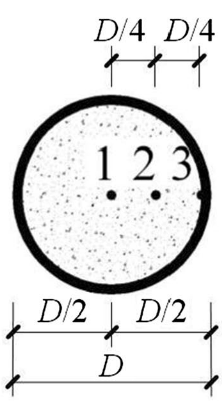


(b) Failure mode of specimens from square composite columns

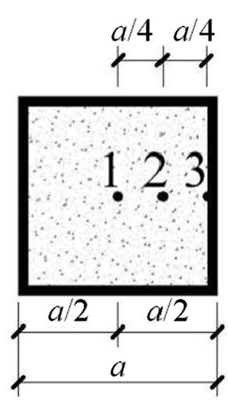
(c) Specimen on the compression machine after test

Fig. 4 Damage of specimens after test

Fig. 3 Thermocouples set for composite column



(a) Thermocouples set for circular column



(b) Thermocouples set for square column

Table 2 Comparisons of compressive strength of UHSC post-fire (Specimens from circular composite columns)

Specimen	$f_{cr}(T)$ (MPa)	f_c (MPa)	$f_{cr}(T)/f_c$	T_{max} (°C)
CC-2-2X	115	161	0.71	256
CC-2-3X	120	165	0.73	160
CC-2-4X	106	168	0.63	332
CC-2-5S	85	164	0.52	496
CC-2-5X	83	164	0.51	496
CC-2-6X	122	163	0.75	72
CC-3-1X	107	181	0.59	376
CC-3-2S	133	181	0.73	62
CC-3-2X	139	181	0.77	62
CC-4-1X	126	180	0.7	277

Table 3 Comparisons of compressive strength of UHSC post-fire (Specimens from square composite columns)

Specimen	$f_{cr}(T)$ (MPa)	f_c (MPa)	$f_{cr}(T)/f_c$	T_{max} (°C)
SC-2-1S	130	163	0.80	159
SC-2-2S	123	174	0.71	275
SC-2-3S	125	173	0.72e	258
SC-2-4S	116	170	0.68	292
SC-2-4X	117	170	0.69	292
SC-2-5S	101	166	0.61	357
SC-2-5X	103	166	0.62	357
SC-2-6X	131	166	0.79	161

Table 4 Comparisons of elastic modulus of UHSC post-fire (Specimens from circular composite columns)

Specimen	$E_{cr}(T)$ (GPa)	E_c (GPa)	$E_{cr}(T)/E_c$	T_{max} (°C)
CC-2-2X	40	65	0.62	256
CC-2-3X	50		0.77	160
CC-2-4X	30		0.46	332
CC-2-5S	22		0.34	496
CC-2-5X	23		0.35	496
CC-2-6X	53		0.82	72
CC-3-1X	28		0.43	376
CC-3-2S	54		0.83	62
CC-3-2X	55		0.85	62
CC-4-1X	36		0.55	277

Table 5 Comparisons of elastic modulus of UHSC post-fire (Specimens from square composite columns)

Specimen	$E_{cr}(T)$ (GPa)	E_c (GPa)	$E_{cr}(T)/E_c$	T_{max} (°C)
SC-2-1S	47	65	0.72	159
SC-2-2S	31		0.48	275
SC-2-3S	34		0.52	258
SC-2-4S	27		0.42	292
SC-2-4X	28		0.43	292
SC-2-5S	21		0.32	357
SC-2-5X	22		0.34	357
SC-2-6X	46		0.71	161

Table 6 Comparisons of peak strain of UHSC post-fire (Specimens from circular composite columns)

Specimen	$\varepsilon_{cr}(T)$	ε_0	$\varepsilon_{cr}(T)/\varepsilon_0$	T_{max} (°C)
CC-2-2X	3553	2300	1.54	256
CC-2-3X	3238		1.41	160
CC-2-4X	3661		1.59	332
CC-2-5S	4164		1.81	496
CC-2-5X	4139		1.80	496
CC-2-6X	2503		1.09	72
CC-3-1X	3855		1.68	376
CC-3-2S	2444		1.06	62
CC-3-2X	2431		1.06	62
CC-4-1X	3573		1.55	277

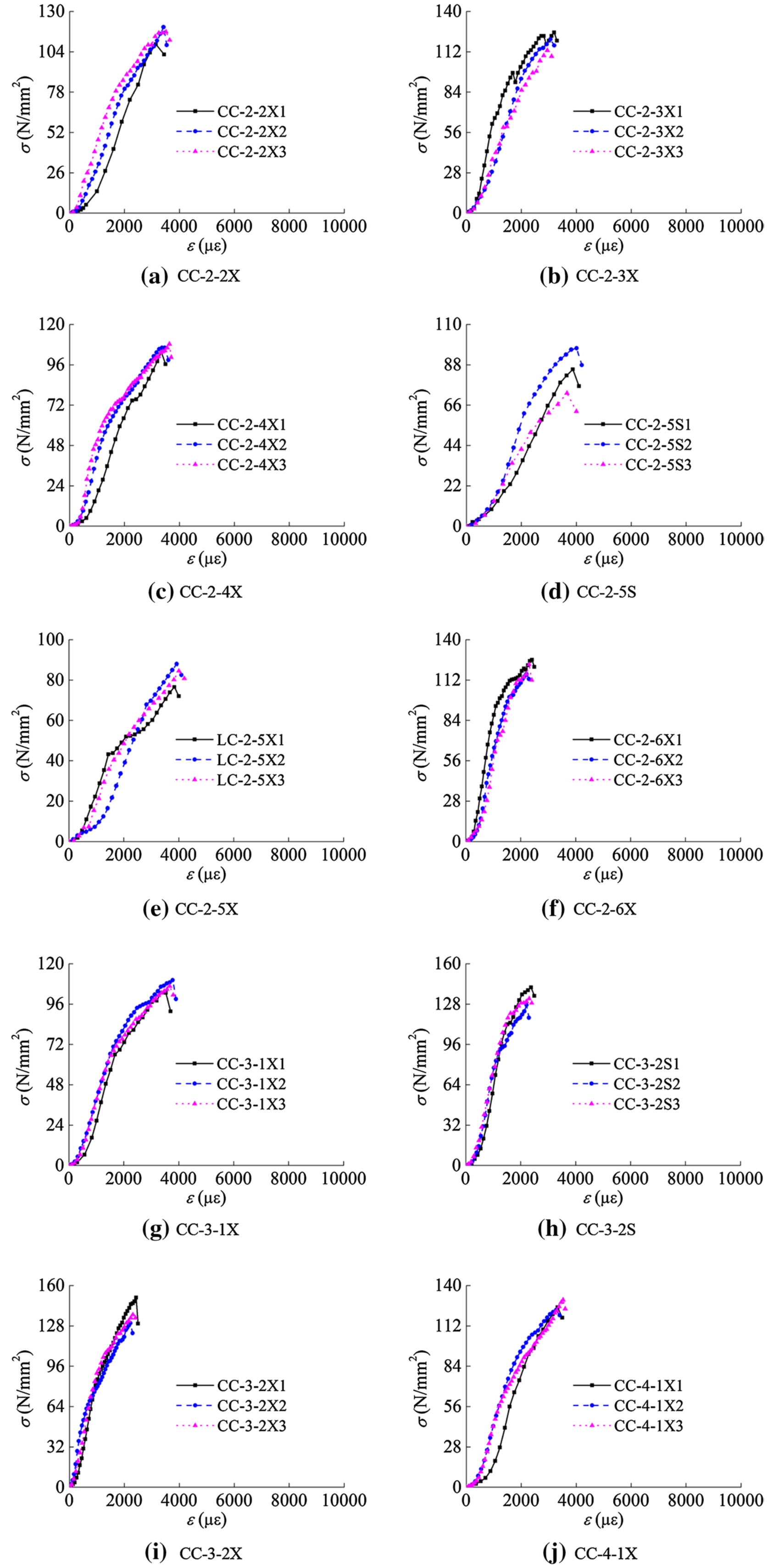
Table 7 Comparisons of peak strain of UHSC post-fire (Specimens from square composite columns)

Specimen	$\varepsilon_{cr}(T)$	ε_0	$\varepsilon_{cr}(T)/\varepsilon_0$	T_{max} (°C)
SC-2-1S	3169	2300	1.38	159
SC-2-2S	3638		1.58	275
SC-2-3S	3554		1.55	258
SC-2-4S	3827		1.66	292
SC-2-4X	3763		1.64	292
SC-2-5S	3983		1.73	357
SC-2-5X	3915		1.70	357
SC-2-6X	3245		1.41	161

3.2 Stress–Strain Curves for Standard Specimens

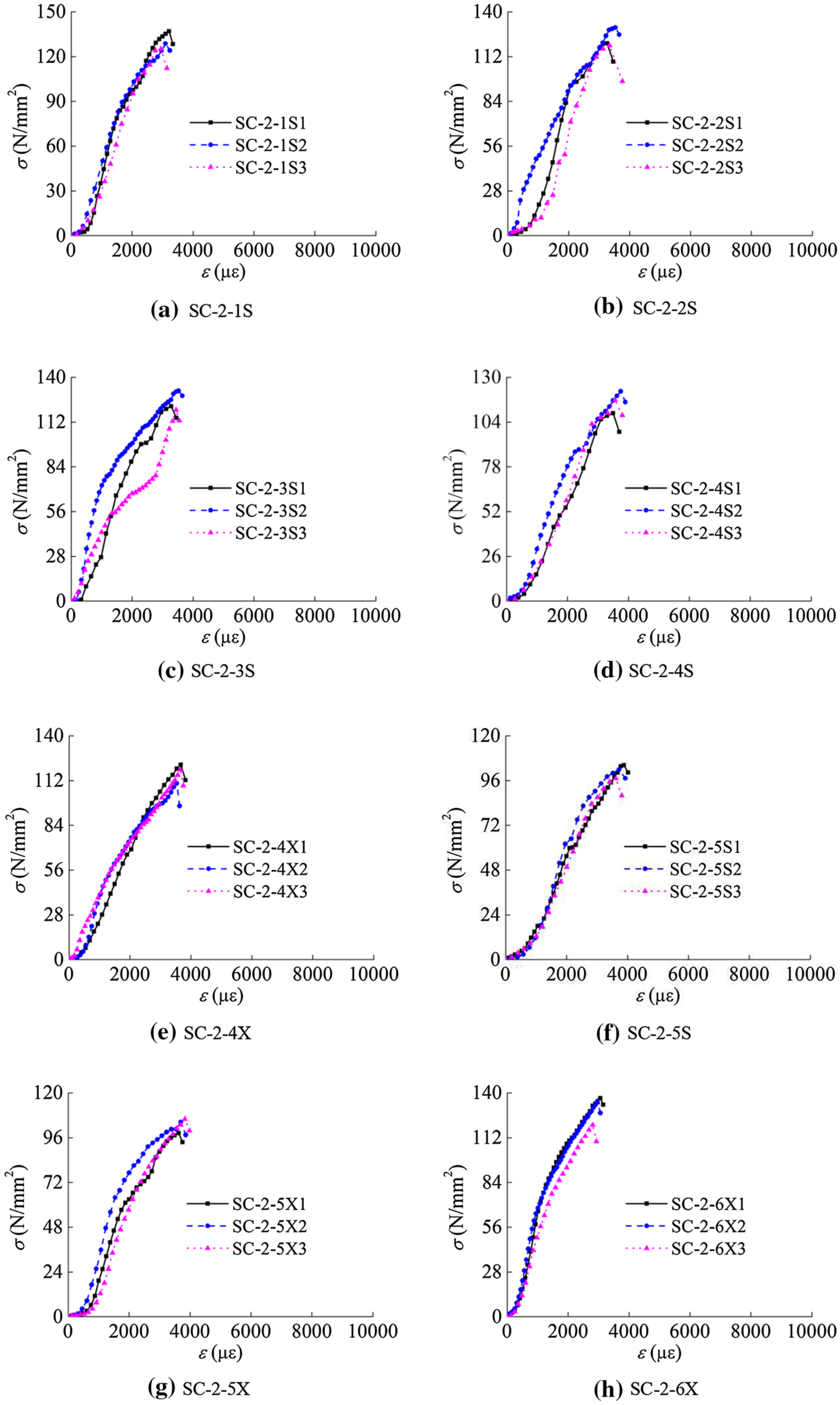
The stress–strain curves of standard specimens from circular and square composite columns after experiencing different temperatures were shown in Figs. 5a–j and 6a–h, respectively. Different from the concrete specimen only tested at high temperature, the UHSC core samples here experienced the combined action of high temperature, initial load and steel pipe constraint. It can be seen from the test results that when the heating temperature of core concrete was less than 400 °C, the strength of UHSC still changed greatly. This was because the load was applied to the composite columns with the temperature rising at the period of fire resistance experiment. It accelerated the reduction of the strength and elastic modulus of the inner core concrete.

Fig. 5 Stress–strain curves of standard specimens obtaining from circular composite columns



(a) CC-2-2X **(b)** CC-2-3X **(c)** CC-2-4X **(d)** CC-2-5S **(e)** CC-2-5X **(f)** CC-2-6X **(g)** CC-3-1X **(h)** CC-3-2S **(i)** CC-3-2X **(j)** CC-4-1X

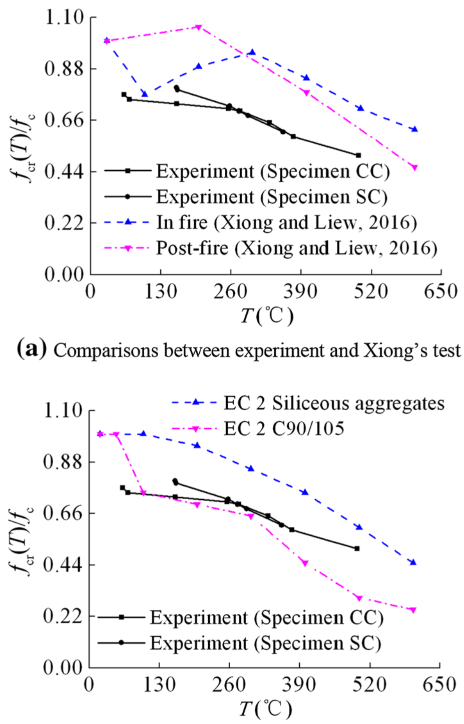
Fig. 6 Stress–strain curves of standard specimens obtaining from square composite columns



3.3 Reduction of Compressive Strength

Figure 7A and b showed the comparison of test results and the data from references (Xiong & Liew, 2016; Eurocode 2, 2004).

As was showed in Fig. 7a and b, the compressive strength of UHSC from specimen CC (circular column) and specimen SC (square column) post-fire was decreased more serious than that cylinder specimen (100 × 200 mm) in fire. In other words, the damage of UHSC from



(a) Comparisons between experiment and Xiong's test

(b) Comparisons between experiment and EC 2

Fig. 7 Comparisons between experiment and references

specimen CC and specimen SC was more serious undergoing the same temperature. This was because the UHSC suffered high temperature and pre-load before cooling down and testing. For specimen CC, after 100 °C, the strength reduction coefficient of UHSC is 0.74, but the strength reduction coefficient of cylinder specimen (100 × 200 mm) in and after fire is 0.77 and 1.03 respectively. The strength reduction coefficient of UHSC is 0.68, but the strength reduction coefficient of cylinder specimen (100 × 200 mm) in and after fire is 0.95 and 0.92 respectively, with the history temperature 300 °C. When the history temperature is 500 °C, the strength reduction coefficient of UHSC is 0.51, but the strength reduction coefficient of cylinder specimen (100 × 200 mm) in and after fire is 0.71 and 0.62 respectively. For specimen SC, after 200 °C, the strength reduction coefficient of UHSC is 0.76, but the strength reduction coefficient of cylinder specimen (100 × 200 mm) in and after fire is 0.89 and 1.06 respectively. The strength reduction coefficient of UHSC is 0.67, but the strength reduction coefficient of cylinder specimen (100 × 200 mm) in and after fire is 0.95 and 0.92 respectively, with the temperature reaching 300℃. This indicated that with the increase of the temperature experienced by UHSC, the reduction of the compressive strength of concrete in tubes was worse, including the specimens from circular and square composite columns.

3.4 Simple Equations for Residual Strength of UHSC Post-fire

Based on the data from experiment, the simple equation for residual strength of UHSC post-fire can be described as follows,

For specimens from circular composite columns ($R^2 = 0.9649$):

$$\frac{f_{cr}(T)}{f_c} = 0.7637 + 2 \times 10^{-5}T - 10^{-6}T^2, \quad 20^\circ\mathrm{C} \le T \le 800^\circ\mathrm{C} \tag{1}$$

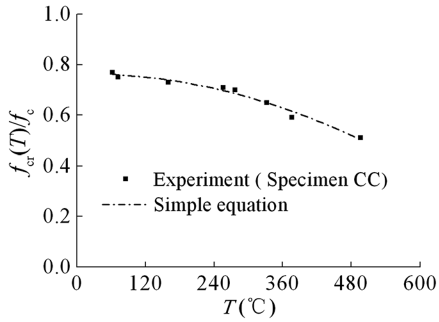
For specimens from square composite columns ($R^2 = 0.9962$):

$$\frac{f_{cr}(T)}{f_c} = 0.8629 - 2 \times 10^{-4}T - 10^{-6}T^2, \quad 20^\circ\mathrm{C} \le T \le 800^\circ\mathrm{C} \tag{2}$$

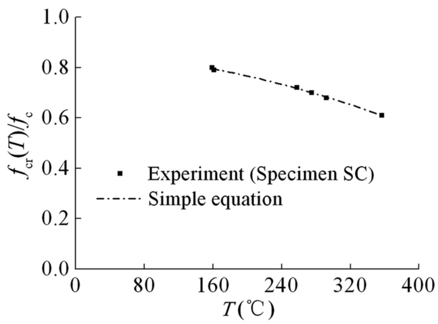
R^2 is an indicator of the fitting degree of the trend line, known as the determination coefficient. Its value can reflect the fitting degree between the estimated value of the trend line and the corresponding actual data. The higher the fitting degree, the higher the reliability of the trend line. The value of R^2 ranges from 0 to 1. When R^2 is 1 or close to 1, the trend line has the high reliability. Otherwise, the trend line has low reliability. Here it indicated that the Eqs. (1) and (2) had acceptable reliability according the value of R^2.

According to Eqs. (1) and (2), Fig. 8a, b showed the comparison of data from experiment and calculation results by simple equation. For specimen CC and SC, the residual sum of the squares between the calculated values and the experimental values is 1.37×10^{-3}, 5.82×10^{-5}, respectively. It showed that the simple equations proposed here is in good agreement with the experimental values of compressive strength reduction coefficient of UHSC in tubes after fire.

Figure 9 showed the comparison of calculation results by simply equation and data from references (Li & Guo, 1993; Xu & Xu, 2000). At the beginning of temperature, according to simply equation, the calculation results was difference from that in reference, but was well agreed with each other after 400℃. This was because the pre-load was applied on the composite columns during fire resistance test. It caused irreversible damage to the UHSC inside the steel pipe after the specimens cooling down. The residual strength was decreased with the temperature the specimens experienced rising. It was only 20% of that in room temperature when the highest temperature reached 800 °C.



(a) Standard specimens from circular composite columns



(b) Standard specimens from square composite columns

Fig. 8 Comparison of strength reduction between experiment and simple equation

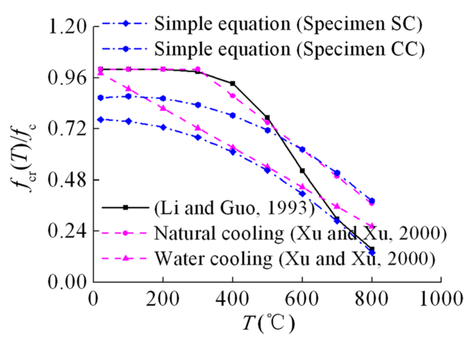


Fig. 9 Comparison of simple equation and references

3.5 Reduction of Elastic Modulus and Simple Equations Post-fire

Figure 10 showed the comparison of elastic modulus between experiment results and the data from the references (Xiong & Liew, 2016). Seen from Fig. 10, the residual elastic modulus of UHSC in tube after fire was lower than that of UHSC in and after fire. This was also because the UHSC in steel tube had been subjected to the combination action of high temperature and load before the composite columns cooling down. For specimen CC, with the temperature up to 100 °C, the elastic modulus reduction coefficient of UHSC is 0.8, but the elastic modulus reduction coefficient of cylinder specimen (100 × 200 mm) in and after fire is 0.84 and 1.97, respectively. The elastic modulus reduction coefficient of UHSC is 0.51, but the elastic modulus reduction coefficient of cylinder specimen (100 × 200 mm) in and after fire is 0.75 and 0.7 respectively, with the temperature reaching 300 °C. When the temperature is 500 °C, the elastic modulus reduction coefficient of UHSC is 0.34, but the elastic modulus reduction coefficient of cylinder specimen (100 × 200 mm) in and after fire is 0.46 and 0.42 respectively. For specimen SC, with the temperature achieving 200 °C, the elastic modulus reduction coefficient of UHSC is 0.63, but the elastic modulus reduction coefficient of cylinder specimen (100 × 200 mm) in and after fire is 0. 9 and 0.92 respectively. The elastic modulus reduction coefficient of UHSC is 0.41, but the elastic modulus reduction coefficient of cylinder specimen (100 × 200 mm) in and after fire is 0.75 and 0.7 respectively, with the temperature reaching 300 °C. This demonstrated that with the increase of the temperature experienced by UHSC, the elastic modulus reduction of concrete in tubes was worse.

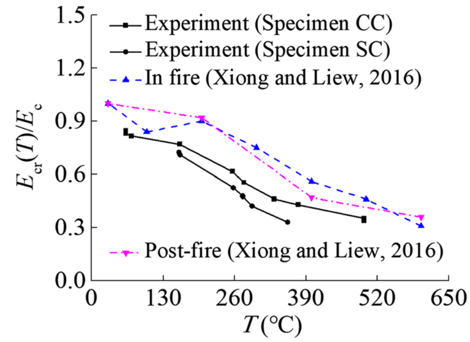


Fig. 10 Comparisons of elastic modulus between experiment and Xiong's test

Based on the data from experiment, the simple equation for elastic modulus of UHSC post-fire can be described as follows,

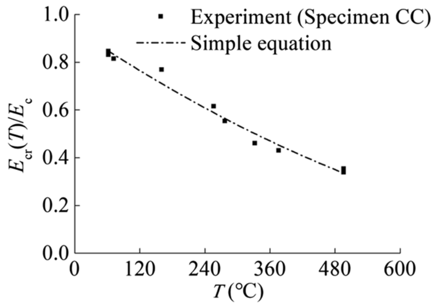
For specimens from circular composite columns ($R^2 = 0.9749$):

$$\frac{E_{cr}(T)}{E_c} = 0.9417 - 1.5 \times 10^{-3}T + 6 \times 10^{-7}T^2, \quad 20^\circ\mathrm{C} \le T \le 800^\circ\mathrm{C} \tag{3}$$

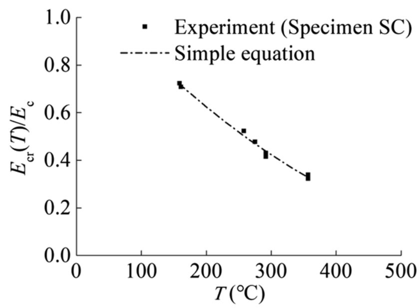
For specimens from square composite columns ($R^2 = 0.9895$):

$$\frac{E_{cr}(T)}{E_c} = 1.1894 - 3.3 \times 10^{-3}T + 3 \times 10^{-6}T^2, \quad 20^\circ\mathrm{C} \le T \le 800^\circ\mathrm{C} \tag{4}$$

According to Eqs. (3) and (4), the elastic modulus reduction coefficient of UHSC in tube varies with temperature as shown



(a) Standard specimens from circular composite columns



(b) Standard specimens from square composite columns

Fig. 11 Comparison of elastic modulus reduction between experiment and simple equation

in Fig. 11a and b, and was compared with the experimental value after fire. For specimen CC and SC, the residual sum of the squares between the calculated values and the experimental values is 7.17×10^{-3}, 1.22×10^{-3} respectively. It indicated that the simple equations proposed here is in good agreement with the experimental values of elastic modulus reduction coefficient of UHSC in tubes after fire.

3.6 Peak Strain and Simple Equations Post-fire

Based on the data from experiment, the simple equation for elastic modulus of UHSC post-fire can be described as follows,

For specimens from circular composite columns ($R^2=0.9817$):

$$\frac{\varepsilon_{cr}(T)}{\varepsilon_0} = 0.8863 + 3.2\times10^{-3}T - 3\times10^{-6}T^2, \quad 20^\circ\text{C} \le T \le 800^\circ\text{C} \tag{5}$$

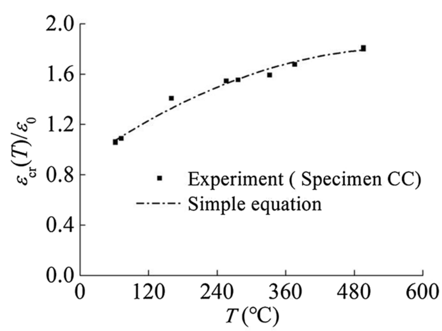
For specimens from square composite columns ($R^2=0.9599$):

$$\frac{\varepsilon_{cr}(T)}{\varepsilon_0} = 1.036 + 2.5\times10^{-3}T - 2\times10^{-6}T^2, \quad 20^\circ\text{C} \le T \le 80^\circ\text{C} \tag{6}$$

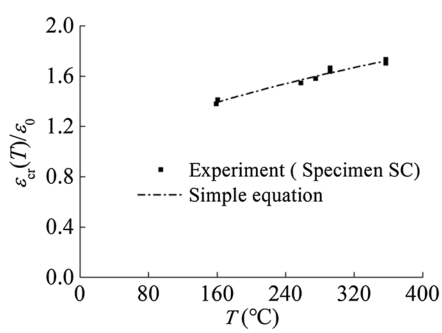
According to Eqs. (5) and (6), the peak strain coefficient of UHSC in tube varies with temperature as shown in Fig. 12a, b, and was compared with the experimental value after fire. Compared the calculated value with the experimental value, the residual sum of the squares is 1.11×10^{-2}, 3.4×10^{-3} for specimens CC and SC, respectively. It indicated that the simple equations proposed here is in good agreement with the experimental values of peak strain coefficient of UHSC in tubes after fire.

3.7 Dimensionless Stress–Strain Equation

Compared with normal temperature, the UHSC mechanics index changed post-fire and the data dispersed widely, but the curves of stress–strain relationship were almost the same whether UHSC specimens were from circular tube or square tube according to the perspective of the dimensionless results of experimental data, as shown in Fig. 13. The simple equation showed a good agreement with experiment. In the test, the brittle failure of standard cylindrical UHSC appeared after the peak stress point and the data after the peak point was difficult to collect. Therefore, based on the test results and the recommended formula in literature (Wu et al., 2000), the dimensionless stress–strain expression of UHSC was obtained as follows:



(a) Standard specimens from circular composite columns



(b) Standard specimens from square composite columns

Fig. 12 Comparison of peak strain between experiment and simple equation

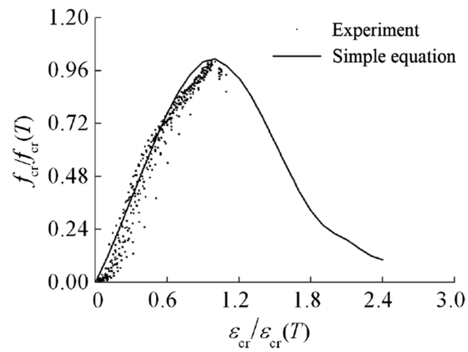


Fig. 13 Comparisons between experiment and the dimensionless stress–strain equation

$$Y = \begin{cases} 1.0666x + 0.9579x^2 - 1.0105x^3 & 0 \le x \le 1 \\ -2.535 + 8.448x + 6.291x^2 - 1.378x^3 & 1 \le x \le 2 \\ -22.651 + 32.252x - 15.008x^2 + 2.3x^3 & 2 \le x \le 2.5 \end{cases} \tag{7}$$

where, $x=\varepsilon_{cr}/\varepsilon_{cr}(T)$, $Y=f_{cr}/f_{cr}(T)$. ε_{cr} is strain of UHSC in tube. f_{cr} is stress of UHSC in tube. $\varepsilon_{cr}(T)$ is peak strain of UHSC in tube post-fire. $f_{cr}(T)$ is peak stress of UHSC in tube post-fire.

4 Conclusion

Based on the experimental study and the analysis of the test results, the following conclusions can be drawn:

(1) With the presented results out of the test program, it could be shown that the compressive strength and elastic modulus of UHSC decreased more serious with the temperature the specimens suffered higher and higher. Compared to Eurocode 2, the compressive strength reduction coefficient of was smaller than that of normal siliceous aggregates concrete, but was bigger than that of C90/105 high strength concrete when the temperature exceeded 150 °C. This might be because that the constraint of steel tube slowed down the damage of UHSC inside.

(2) A severe loss of strength and elastic modulus was observed for all the concretes after experience to 500 °C, despite their good mechanical properties at room temperature. Consequently, the range of 300–500 °C is more critical for UHSC. With the same temperature, the residual compressive strength of UHSC inside steel tube was lower than that of bare UHSC in fire and post-fire. This was because that the UHSC suffered pre-load with the steel tube in fire before experiment post-fire. The pre-load on composite columns made the compressive strength of UHSC inside decayed obviously.

(3) Compared to CC, the material deterioration of SC was even more, especially for elastic modulus. This might because the circular steel tubes provide stronger constraints on the internal concrete than square ones. Based on the experiment results of UHSC, simple equations were proposed to depict the residual compressive strength, elastic modulus and peak strain of UHSC inside the steel tube post-fire, respectively. The dimensionless stress–strain equation was presented to describe the stress–strain relationship of UHSC post-fire. These were helpful to reveal the multiaxial mechanical properties of UHSC inside tube post-fire, and provided the experimental and theory foundations (testing data and correlated formula) for structural safety assessment and maintenance post-fire, and even for fire-resistant structural design.

Acknowledgements The research work described in this paper is part of Project 52038006 supported by the State Key Program of National Natural Science Foundation of China, Project ZR2021ME190 supported by Natural Science Foundation of Shandong Province of China, Project XTP201919 supported by Shandong Co-Innovation Center for Disaster Prevention and Mitigation of Civil Structures, Project XNBS1929 supported by Doctoral Research Fund of Shandong Jianzhu University. The financial support is highly appreciated. The authors are grateful to Professor J. Y. Richard Liew, Department of Civil and Environmental Engineering, National University of Singapore, for his useful comments.

References

Aslani, F., & Samali, B. (2013a). Constitutive relationships for steel fibre reinforced concrete at elevated temperatures. *Fire Technology, 50*(5), 1249–1268.

Aslani, F., & Samali, B. (2013b). High strength polypropylene fibre reinforcement concrete at high temperature. *Fire Technology, 50*(5), 1229–1247.

ASTM C 469-02 (2002). Standard test method for static modulus of elasticity and Poisson's ratio of concrete in compression. ASTM International, United States.

Bamonte, P., & Gambarova, P. G. (2010). Thermal and mechanical properties at high temperature of a very high-strength durable concrete. *Journal of Materials in Civil Engineering, 22*(6), 545–555.

Cai, R. J., & Ye, H. L. (2021). Clinkerless ultra-high strength concrete based on alkali-activated slag at high temperatures. *Cement and Concrete Research, 145*, 106465.

CECS 03:2007. (2007). Technical specification for testing concrete strength with drilled core. China.

Chung, K. S., Kim, J. H., & Yoo, J. H. (2013). Experimental and analytical investigation of high-strength concrete-filled steel tube square columns subjected to flexural loading. *Steel and Composite Structures, 14*(2), 133–153.

Du, Y., Qi, H. H., Huang, S. S., & Liew, J. Y. R. (2020). Experimental study on the spalling behaviour of ultra-high strength concrete in fire. *Construction and Building Materials, 258*, 120334.

ECS (2004), Eurocode 2: Design of concrete structures-Part 1–2, General rules-structural fire design, EN 1992–1–2, European Committee for Standardization.

Huang, L., Liu, J. C., Cai, R. J., & Ye, H. L. (2021). Mechanical degradation of ultra-high strength alkali-activated concrete subjected to repeated loading and elevated temperatures. *Cement and Concrete Composites, 121*, 104083.

Karimi, A., & Nematzadeh, M. (2020). Axial compressive performance of steel tube columns filled with steel fiber-reinforced high strength concrete containing tire aggregate after exposure to high temperatures. *Engineering Structures, 219*, 110608.

Kim, Y. S., Ohmiya, Y., Kanematsu, M., & Kim, G. Y. (2016). Effect of aggregate on residual mechanical properties of heated ultra-high-strength concrete. *Materials and Structures, 49*(9), 3847–3859.

Kodur, V. K. R. (1998). Performance of high strength concrete-filled steel columns exposed to fire. *Canadian Journal of Civil Engineering, 25*(6), 975–981.

Lee, T., Kim, G., Choe, G., Hwang, E., Lee, J., Ryu, D., & Nam, J. (2020). Spalling Resistance of fiber-reinforced ultra-high-strength concrete subjected to the ISO-834 standard fire curve: Effects of thermal strain and water vapor pressure. *Materials, 13*(17), 3792.

Li, W., & Guo, Z. H. (1993). Experimental investigation of strength and deformation of concrete at elevated temperature. *Journal of Building Structures, 14*(1), 8–16. In Chinese.

Li, Y., Tan, K. H., & Yang, E. H. (2018). Influence of aggregate size and inclusion of polypropylene and steel fibers on the hot permeability of ultra-high performance concrete (UHPC) at elevated temperature. *Construction and Building Materials, 169*, 629–637.

Liew, J. Y. R., Xiong, M. X., & Xiong, D. X. (2014). Design of high strength concrete filled tubular columns for tall buildings. *International Journal of High-Rise Buildings, 3*(3), 1–7.

Liu, K., Wu, C. Q., Li, X. B., Liu, J., Tao, M., Fang, J. G., & Xu, S. C. (2021). The influences of cooling regimes on fire resistance of ultra-high performance concrete under static-dynamic coupled loads. *Journal of Building Engineering, 44*, 103336.

Lyu, X., Shu, G. P., & Du, E. F. (2020). Parameters effect on predicting fire resistance of ultra-high strength concrete filled protected square steel tubular columns. *International Journal of Steel Structures, 20*(5), 1783–1795.

Lyu, X., Shu, G. P., Liew, J. Y. R., & Du, E. F. (2018). Fire resistance of steel tubular columns infilled with ultra-high strength concrete. *Advanced Steel Construction, 14*(3), 438–460.

Romero, M. L., Espinós, A., Portolés, J. M., Hospitaler, A., & Ibañez, C. (2015). Slender double-tube ultra-high strength concrete-filled tubular columns under ambient temperature and fire. *Engineering Structures, 99*, 536–545.

Song, T. Y., & Xiang, K. (2020). Performance of axially-loaded concrete-filled steel tubular circular columns using ultra-high strength concrete. *Structures, 24*, 163–176.

Wang, T., Yu, M., Zhang, X., Cheng, S., & Liu, S. (2022b). Post-fire mechanical behaviour of ultra-high-performance concrete-filled steel tube (UHPCFST) stub columns under compression. *Journal of Constructional Steel Research, 196*, 107384.

Wang, T., Yu, M., Zhang, X., & Ye, J. (2022a). Experimental study on random temperature field of ultra-high performance concrete filled steel tube columns under elevated temperature. *Composite Structures, 289*, 115445.

Wu, B., Yuan, J., & Wang, G. Y. (2000). Experimental research on the mechanical properties of HSC after high temperature. *China Civil Engineering Journal, 33*(2), 8–12.

Xiong, M. X., & Liew, J. Y. R. (2016). Mechanical behavior of ultra-high strength concrete at elevated temperatures and fire resistance of ultra-high strength concrete filled steel tubes. *Materials & Design, 104*, 414–427.

Xiong, M. X., & Liew, J. Y. R. (2021). Fire resistance of high-strength steel tubes infilled with ultra-high-strength concrete under compression. *Journal of Constructional Steel Research, 176*, 106410.

Xiong, M. X., Xiong, D. X., & Liew, J. Y. R. (2017). Flexural performance of concrete filled tubes with high tensile steel and ultra-high strength concrete. *Journal of Constructional Steel Research, 132*, 191–202.

Xu, P., Cui, Y. H., Dai, J. F., Zhang, M. X., & Ding, Y. H. (2022a). High-temperature deterioration mechanism of textile-reinforced concrete with different cementitious materials. *Journal of Materials in Civil Engineering, 34*(1), 04021388.

Xu, Y., & Xu, Z. S. (2000). Experiment investigation of strength of concrete after High temperature. *Concrete, 2*, 44–45. In Chinese.

Xu, Z., Li, J., Qian, H., & Wu, C. (2022). Blast resistance of hybrid steel and polypropylene fibre reinforced ultra-high performance concrete after exposure to elevated temperatures. *Composite Structures, 294*, 115771.