Temperature Field Analysis of CFRP-Reinforced Concrete Beams Under Fire

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Abstract: The high-temperature thermal performance parameters of CFRP were summarised from overseas research on fire resistance tests of CFRP-reinforced concrete structures. Numerical simulations of the temperature field of CFRP-reinforced reinforced concrete beams under different conditions (without and with fire protection layer) and different working conditions (in the form of fire protection coating) at high fire temperatures were carried out using Abaqus software.

Keywords: CFRP; Temperature field; ABAQUS; Fire

1. INTRODUCTION

In recent years, Carbon Fiber Reinforced Plastic (CFRP) has been favoured in the field of building reinforcement for its high strength, high efficiency, lightweight, durability and ease of construction[1], and one of the most common forms of reinforcement is externally bonded The most common form of reinforcement is externally bonded reinforced (EBR), in which CFRP material is directly bonded to the external surface of the structure to play a reinforcing role. At present, China and the world have formed a relatively complete system of standards and specifications for the application of CFRP in construction projects[2], covering the following main technical fields: concrete reinforcement, masonry reinforcement, steel reinforcement, reinforced concrete structures with CFRP tendons and pre-stressed CFRP tendons, composite pipe assemblies and composite profile assemblies[5]. The mechanical properties of CFRP-constrained concrete have also been extensively investigated by researchers at home and abroad, but most of them are limited to the ambient temperature case. In the event of fire, the structural system of the building must be strong enough to maintain sufficient stability for a certain period[7] so that the affected people can be safely evacuated. Therefore, from a safety point of view, it is necessary to study the fire resistance of the structure based on the normal performance of the building.

1.1. Structural properties of concrete

Du Hongxiu et al[12] studied the effect of temperature on the strength of concrete after high temperatures. The results show that when concrete was subjected to temperatures below 300°C, its strength was the same as that at room temperature, and the strength of concrete decreased by 10%-20% when the temperature was between 300 and 400°C. When the temperature reached above 400°C the reduction rate of concrete strength accelerated and was accompanied by the generation of surface cracks. Yan Jihong et al[13] analysed the effect of temperature and the resting time experienced by concrete after high-temperature tests on its compressive strength through tests. The research has shown that temperature has a large effect on the compressive strength of concrete, which decreases very little when the temperature experienced by concrete is below 300°C and begins to fall sharply after it is above 300°C. And Mohamedbhai[14] proposed the idea that concrete only needs a constant temperature of 3 hours to achieve a uniform temperature field.

1.2. Structural properties of CFRP

Täljsten[15] carried out a comparative test study of the flexural performance of reinforced concrete slabs reinforced with carbon fibre composite panels and reinforced concrete slabs reinforced with carbon fibre composite meshes, both of which obtained similar load-deflection curves and a 60% increase in flexural load capacity compared with unreinforced slabs. The test parameters were the cross-sectional area of the basalt fibre composite mesh and the bonded anchorage length of the reinforcement layer. The test results show that the damage pattern of all the reinforced beams is that the basalt fibre composite mesh is pulled off in the mid-span area that there is no peeling of the reinforcement layer about the original concrete, and that the tensile strength of the composite is fully utilised.

1.3. Structural performance of CFRP composite reinforced concrete

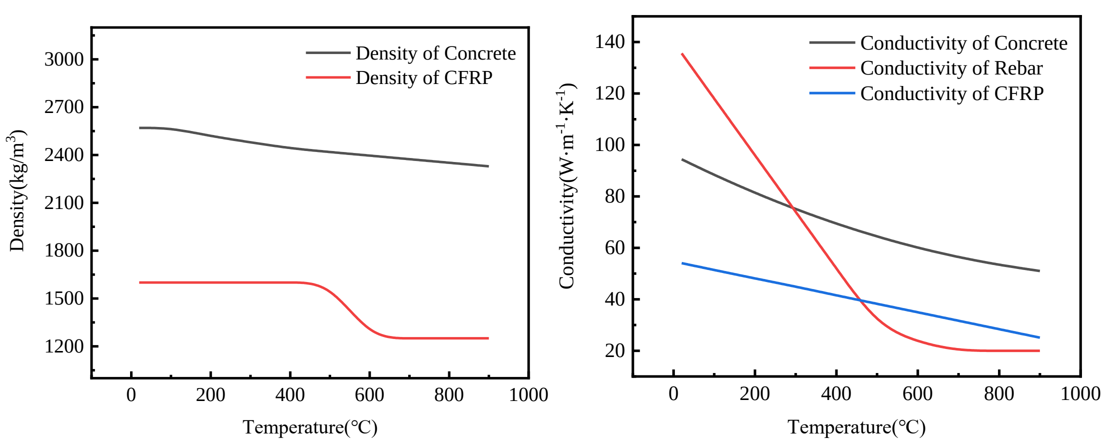
Adrian Lowe et al[18] investigated the ageing of the carbon fibre composite CBR320/328 at 204°C and 250°C in the interfacial region. The results showed a change in the glass transition temperature of the composite and a loss of weight. The fibre-matrix interface and resin degradation differed between these two temperatures and accelerated ageing did not apply to this composite. As the high-temperature ageing time increased, the fracture energy showed a tendency to increase and then decrease; a slight difference in the relative peak size was found by infrared spectroscopy. Cai Zhenghua[19] conducted a study on the shear performance of the CFRP cloth concrete interface at high temperatures and the organic adhesive softened significantly at 60°C. This leads to the conclusion that organic adhesive bonded to carbon fibre cloth reinforced concrete structures are not resistant to high temperatures.

Based on experimental research, scholars at home and abroad have proposed formulae for calculating the tensile strength and modulus of elasticity of compound materials at different temperatures [错误!未找到引用源。], which are empirical formulae based on the fitting of experimental results.

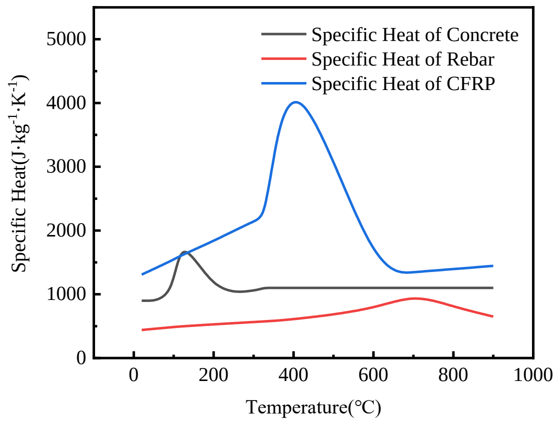
2. METHODS

2.1. Temperature-based material properties

The mechanism of evolution of the mechanical properties of CFRP reinforced concrete slabs depends on the thermal and mechanical properties of the materials at high temperatures. The relationship between the thermal performance parameters of each of these materials (concrete, reinforcement, CFRP, thick fireproof coating) and temperature is shown in Figure 1.



(a) (b)



(c)

Figure 1 Variation of thermal performance parameters of materials as a function of temperature

2.1.1. Concrete

The thermal properties of concrete are defined using its thermal parameters, which mainly include the thermal conductivity of concrete, the coefficient of thermal expansion, the density and its specific heat capacity, all of which are obtained from the relevant formulae in Eurocode EN 1992-1-2. The density of concrete as a function of temperature is given in equation (1)[错误!未找到引用源。]. The unit is kg/m^3 Due to the evaporation of water, the density of concrete decreases slightly with increasing temperature, as shown in Figure 1(a). And the measured density of concrete at room temperature is $\rho(20℃) = 2570\,kg/m^3$.

$$\rho(T) = \begin{cases} \rho(20℃) & 20℃ \le T \le 115℃ \\ \rho(20℃)[1 - 0.02\,(T - 115)/85] & 115℃ < T \le 200℃ \\ \rho(20℃)[0.98 - 0.03\,(T - 200)/200] & 200℃ < T \le 400℃ \\ \rho(20℃)[0.95 - 0.07\,(T - 400)/800] & 400℃ < T \le 1100℃ \end{cases} \tag{1}$$

The thermal conductivity of concrete as a function of temperature is given in equation (2)[错误!未找到引用源。]. The unit is $W/(m \cdot K)$. As shown in Figure 1(b).

$$\lambda(T) = 1.36 - 0.136\left(\frac{T}{100}\right) + 0.0057\left(\frac{T}{100}\right)^2 \tag{2}$$

The specific heat capacity of concrete as a function of temperature is shown in equation (3)[错误!未找到引用源。]. The unit is $J/(kg \cdot K)$. As shown in Figure 1(c). And the moisture content of concrete is taken as 3%, the corresponding maximum specific heat capacity is 2020 $J/(kg \cdot K)$.

$$c(T) = \begin{cases} 900 & 20℃ \le T \le 100℃ \\ 900 + 1120\,(T - 100)/15 & 100℃ < T \le 115℃ \\ 2020 - 12(T - 115) & 115℃ < T \le 200℃ \\ 1000 + (T - 200)/2 & 200℃ < T \le 400℃ \\ 1100 & 400℃ < T \le 1100℃ \end{cases} \tag{3}$$

2.1.2. Reinforcement

The density of the reinforcement does not change with increasing temperature (taken as 7850 kg/m^3)[错误!未找到引用源。], as shown in Figure 1(a).

The thermal conductivity of reinforcement is large and its relationship with temperature is shown in equation (4)错误!未找到引用源。. The unit is $W/(m \cdot K)$. As shown in Figure 1(b).

$$\lambda = \begin{cases} 54 - \dfrac{T}{30} & 20℃ \leq T \leq 800℃ \\ 27.3 & 800℃ \leq T \leq 1100℃ \end{cases} \tag{4}$$

The specific heat capacity of steel bars as a function of temperature is shown in equation (5)错误!未找到引用源。. The unit is $J/(kg \cdot K)$. As shown in Figure 1(c).

$$c = \begin{cases} 425 + 0.773T - (1.69 \times 10^{-3})T^2 + (2.22 \times 10^{-6})T^3 & 20℃ \leq T < 600℃ \\ 666 + \dfrac{13002}{738 - T} & 600℃ \leq T < 735℃ \\ 545 + \dfrac{17820}{T - 731} & 735℃ \leq T < 900℃ \\ 650 & 900℃ \leq T < 1100℃ \end{cases} \tag{5}$$

2.1.3. CFRP

The density of CFRP as a function of temperature is shown in equation (6)[22]. The unit is kg/m^3. As shown in Figure 1(a).

$$\rho(T) = \begin{cases} 1600 & 20℃ \leq T < 510℃ \\ 1600 - \dfrac{350}{28}(T - 510) & 510℃ \leq T < 538℃ \\ 1250 & 538℃ \leq T < 1100℃ \end{cases} \tag{6}$$

The thermal conductivity of CFRP as a function of temperature is shown in equation (7)[22]. The unit is $W/(m \cdot K)$. As shown in Figure 1(b).

$$\lambda(T) = \begin{cases} 1.4 - \dfrac{1.1}{500}T & 200℃ \leq T < 500℃ \\ 0.3 - \dfrac{0.1}{150}(T - 500) & 500℃ \leq T < 650℃ \\ 0.2 & 650℃ \leq T \leq 1100℃ \end{cases} \tag{7}$$

The specific heat capacity of CFRP as a function of temperature is shown in equation (8)[22]. The unit is $J/(kg \cdot K)$. As shown in Figure 1(c).

$$c(T) = \begin{cases} 1250 + \dfrac{950}{325}T & 20℃ \leq T < 325℃ \\ 2200 + \dfrac{2800}{18}(T - 325) & 325℃ \leq T < 343℃ \\ 5000 - \dfrac{150}{167}(T - 343) & 343℃ \leq T < 510℃ \\ 4850 - \dfrac{3585}{28}(T - 510) & 510℃ \leq T < 538℃ \\ 1265 + \dfrac{1385}{2778}(T - 538) & 538℃ \leq T \leq 1100℃ \end{cases} \tag{8}$$

2.1.4. Thick fire protection coatings

At present, the fire protection coating (Fire protection Coating, hereinafter referred to as FC) on the market is a fire protection coating for steel structures, which has a relatively good fire protection effect and is also relatively cheap. According to its coating thickness and performance characteristics, it can be divided into two categories: thin coating type and thick coating type. The mechanism of thick fireproof coating is to use the good thermal insulation of the inherently efficient insulation material of the layer and the heat absorption of the additives to block and consume the heat transfer of fire to the surface of the substrate, thus relieving the substrate from hitting the critical temperature. Therefore, this paper uses thick fireproofing coatings for fire protection of CFRP reinforced concrete beams. However, China's research on thick steel fireproof coatings is still shallow, and only its thermal parameters at room temperature are available, and the changes in its thermal parameters with increasing temperature have not been obtained. Therefore, the thermal performance parameters of the fire protection coatings used for the fire protection of CFRP-reinforced reinforced concrete beams are selected by the literature[22], as follows.

Thermal conductivity $\lambda_{fc} = 0.116\, W/(m \cdot ℃)$

Specific heat capacity $c_{fc} = 1000\, J/(kg \cdot ℃)$

Mass density $\rho_{fc} = 400\, kg/m^3$

2.1.5. Finite element model building and validation

During high fire temperatures, both the fire field temperature and the thermal properties of the member change with time, so the temperature field within the member is a non-linear transient problem, and its governing equation is a non-linear parabolic partial differential equation. To simplify the analysis process, this paper uses ABAQUS software to analyse the temperature field of CFRP-reinforced concrete beams, making the following basic assumptions.

(1) The concrete is assumed to be isotropic with the same thermal conductivity in all directions.

(2) There is no heat generation within the member and the effect of evaporation of water from the concrete is negligible.

(3) The volume of reinforcement in the concrete structure is small and the heat transfer coefficient of the reinforcement is large, so the effect of reinforcement can be ignored in the calculation of the section temperature field.

(4) In the case of reinforced concrete structural rod members, the longitudinal temperature change is generally disregarded and considered as a two-dimensional thermal conductivity problem.

(5) It is assumed that the bond between the concrete and the CFRP and between the CFRP and the fire protection coating is intact.

ABAQUS uses the finite element method to carry out the basic principles of thermal analysis calculations: the object to be treated is first divided into a finite number of units, then the equilibrium equations for each node are solved under certain boundary conditions and initial conditions, the temperature of each node is calculated according to the law of conservation of energy, and then other relevant quantities are solved. In this section, a numerical finite element model is established for the test condition of specimen B2-1 in the literature[9] according to the above method, and a heat transfer simulation analysis of the temperature field is carried out as follows.

(1) Modelling

a) Element type: In the process of temperature field analysis by ABAQUS, DC3D8 (8-node three-dimensional heat transfer unit) was used for concrete, CFRP and thick fireproof coating, and DC1D2 (2-node one-dimensional heat transfer unit) was used for steel reinforcement.

b) Geometrical characteristics and parameters: The concrete beam has dimensions of 1500mm x 100mm x 120mm and is assumed to be subjected to fire on three sides. Relevant parameters such as thermal conductivity, specific heat capacity, density, etc. are entered according to the data provided above.

c) Boundary conditions: The heat transfer conditions between the surface of the CFRP-reinforced reinforced concrete beam and the ambient temperature belong to the third category of boundary conditions. That is $-\lambda\frac{\partial T}{\partial n}|S_3 + S_4 = h(T_s - T_e)$, where T_e is a constant, equal to the ambient temperature; h is called the heat transfer coefficient ($W \cdot m^{-2} \cdot K^{-1}$). It usually consists of two parts: $h = h_c + h_r$, where h_c is the natural convection heat transfer coefficient ($W \cdot m^{-2} \cdot K^{-1}$). h_r is the thermal radiation heat transfer coefficient ($W \cdot m^{-2} \cdot K^{-1}$).

d) Mesh division: As the surface of the member heats up very quickly during the fire, resulting in a large temperature gradient inside the concrete, and the thickness of the CFRP cloth is very thin, a finer cell division and smaller time increment steps are used in the finite element analysis to ensure sufficient accuracy. The concrete, carbon fibre cloth and fire protection layer unit size are all 50mm x 50mm x 20mm. The finite element model of the beam is shown in Figure 2, and its cross-section is shown in Figure 3, where A and B are the end nodes of the outer surface of the CFRP cloth, and C and D are the end nodes of the inner surface of the CFRP cloth.

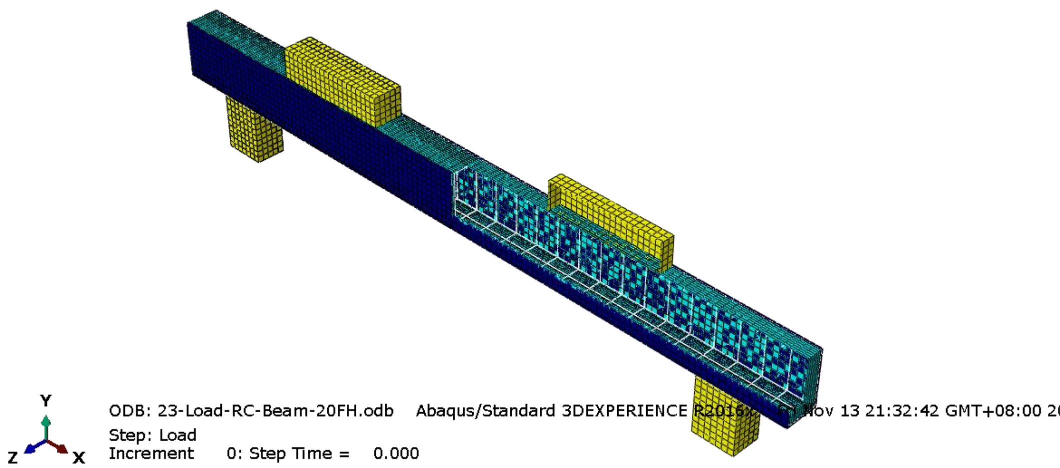


Figure 2 Finite element model of the beam

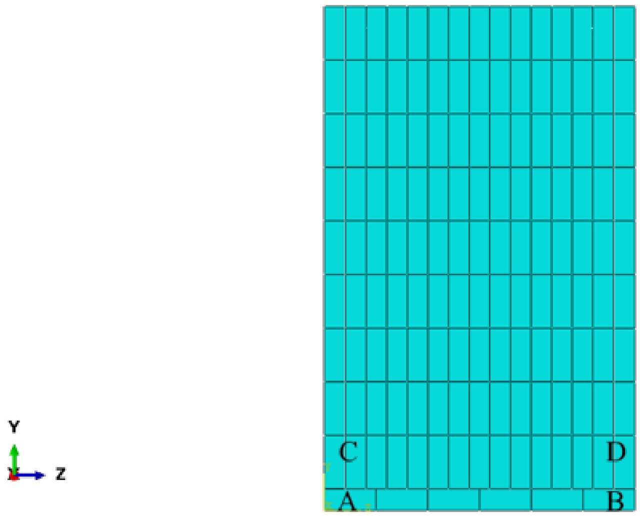


Figure 3 Cross-sectional meshing

(2) Set analysis steps

The equations are solved using Newton's method of iterative solving of non-linear equilibrium equations, with automatic time steps turned on, the initial analysis steps 0.01 and maximum analysis step 2.

(3) Applying loads

In the transient thermal analysis, the load is loaded according to the ISO-834 standard temperature rise curve, as shown in Figure 4. The initial temperature is room temperature and is set to 20°C.

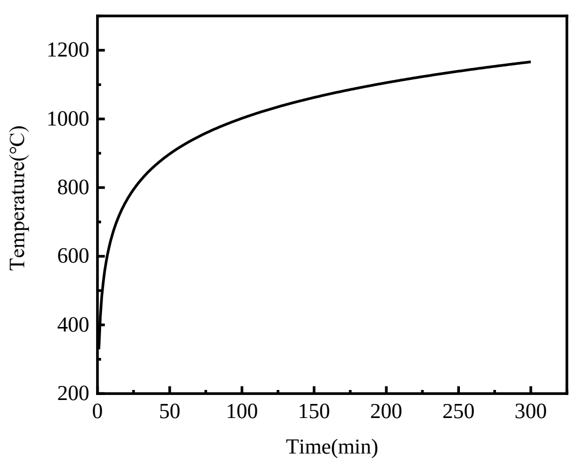


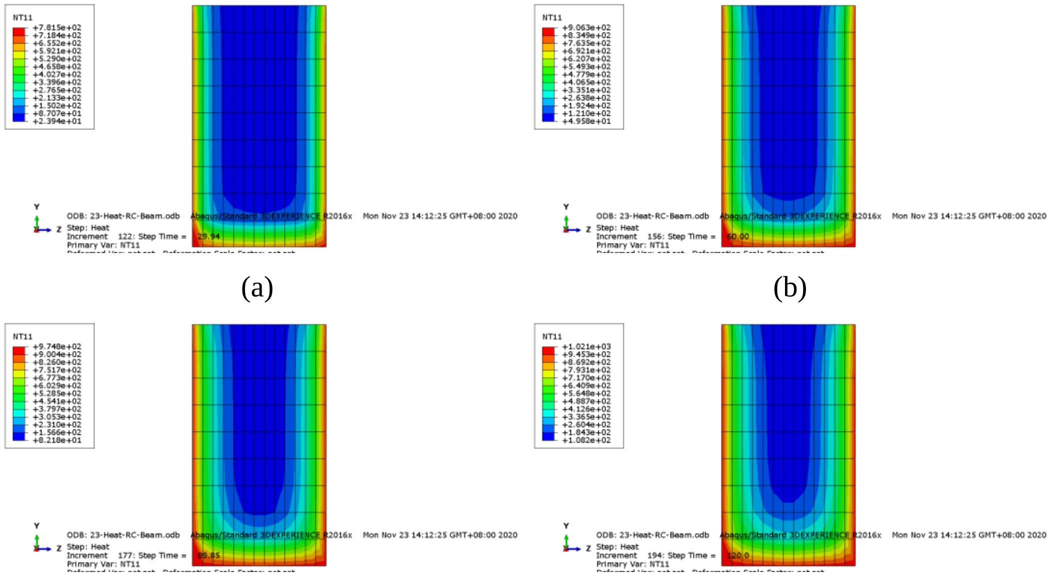
Figure 4 ISO-834 Curve

(4) Submission of assignments

3. RESULTS AND DISCUSSION

When there is no fire protection layer, a total of 15,336 cells are divided, which ensures that the results have sufficient accuracy. Figure 6 shows the temperature field clouds of the cross-section of the CFRP reinforced concrete beam at various moments (30min, 60min, 90min, 120min). It can be seen that with the change of time, the temperature on the fireside of the member grows rapidly, and the heat gradually penetrates the interior of the member through conduction. It was also demonstrated that CFRP has almost no effect on the temperature distribution of the concrete beam.

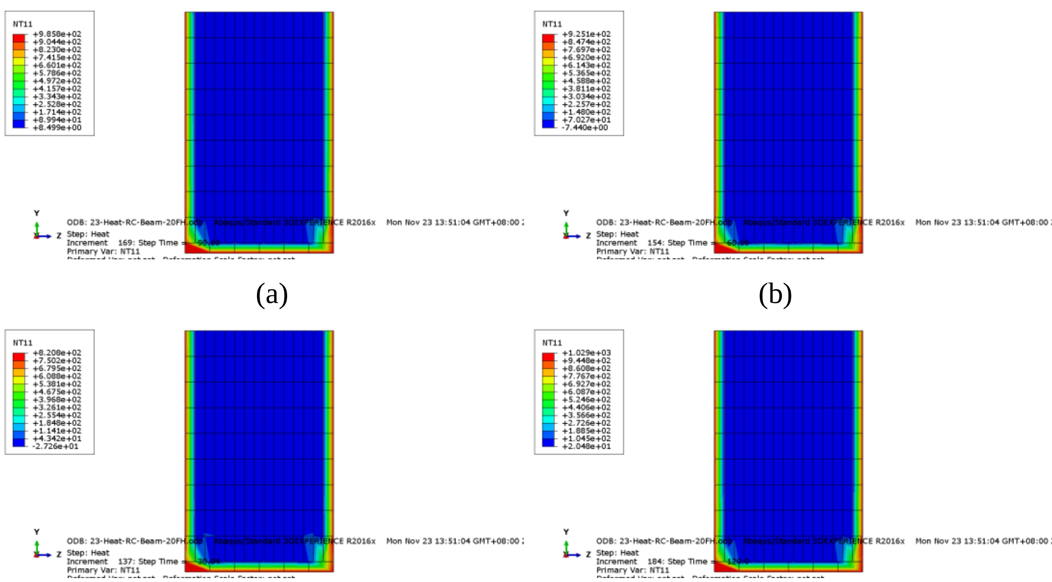
A total of 18,216 cells were divided when the 20 mm thick fire protection coating was used for protection. Figure 5 shows the temperature field clouds of the cross-section of the CFRP reinforced concrete beam at various times (30min, 60min, 90min, 120min). It can be seen that the cross-sectional temperature of the beam is significantly reduced, indicating the excellent fire protection of the fire protection coating.



(a) (b)

(b) (d)

Figure 5 Temperature field distribution on three sides of a concrete beam reinforced with CFRP without fire protection



(a) (b)

(b) (d)

Figure 6 Cloud diagram of the temperature field distribution on three sides of a 20mm thick CFRP reinforced concrete beam subjected to fire

A comparison of the simulation results with those in the literature, shown in Figure 6, shows that the above modelling method has good fitting accuracy, proving the accuracy and reasonableness of the simulation method used in this paper.

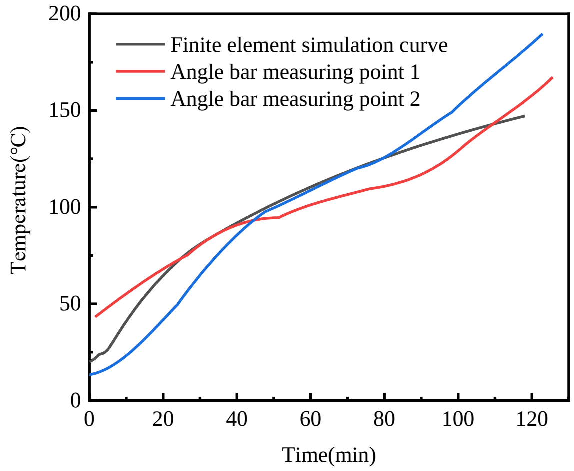


Figure 7 Comparison of test and simulation data

4. CONCLUSIONS

CFRP does not contribute much to the fire resistance of concrete and, for fire-rated elements, fire protection coatings must be added to maximise the mechanical properties of CFRP.

This study contributes to a better understanding of the mechanical properties and fire resistance limits of CFRP-reinforced reinforced concrete structures at elevated temperatures and provides some guidance on the design of CFRP-reinforced structures for fire protection.

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