Simplified Temperature Prediction Method for Insulated CFRP-Strengthened RC Beams Exposed to Standard Fire

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Abstract. This paper presented the finite element (FE) models for thermal analysis of insulated CFRP-strengthened reinforcement concrete beams under standard fire condition. Based on these models, the influences of some parameters (e.g. thermal conductivity, thickness of fireproof coating, time of exposure to fire, and steel bar location) on thermal response were analyzed. The numerical results showed that the temperature at the surface of coating could be calculated by combining standard fire curve and time of fire exposure. The temperature at the surface of concrete beam decreased with the increase of coating thickness and increased linearly with the increase of thermal conductivity. The temperatures at internal concrete were only influenced by the temperature at the surface, the location from the surface and the time of fire exposure. After numerical analysis, a simplified calculating method was presented to predict the temperature value at any points of insulated CFRP-strengthened RC beam section, under standard fire condition. By comparing with the experimental results, the simplified method was well verified.

1. Introduction

Due to the advantages of light weight, high strength, durability and convenient construction, CFRP reinforcement technology has been widely used in practical strengthening engineering. However, the fire resistance of CFRP-strengthened reinforced concrete (RC) structure without fire protection is poor, which brings potential danger to fire safety of the structure. Therefore, fire protection design is needed. In the work of fire protection design, grasping the temperature field accurately of the protected structure is the premise of fire response analysis.

At present, many numerical method and FE analysis were conducted to calculate the temperature field of CFRP-strengthened concrete beams. Bisby and Chowdhury [1] developed an analytical model based on fiber cross-section to evaluate the fire resistance of FRP-wrapped concrete columns. Kodur and Ahemd [2] also developed an analytical model to predict the structural performance of FRP-reinforced concrete beams under fire. Hawleh [3] established a nonlinear FE model by ANSYS software to simulate the fire Williams’ test [4] and prediction results were in good agreement with the experimental data. Dong [5] established a thermal analysis program for insulated FRP-strengthened beams under fire. But a simplified calculation method for section temperature was not given in all the above researches. Based on numerical analysis, Liu [6] established a regression formula for predicting the section temperature with three-side fire protection. However, the main factors were not directly mentioned in Liu’s formula.
For predicting the temperatures more efficiently and simply, several main influencing factors of the section temperature field were considered in this paper. Combined with the theory of heat transfer, some relationship formulas between the temperature value and main influencing factors were presented under the standard fire condition. Finally, a simplified calculating method was presented to predict the temperature value at any points of insulated CFRP-strengthened RC beam section.

2. Calculation of section temperature under one-side fire

According to the analyzing results in the literature [5], the density and specific heat of fireproof coating have less effect on the section temperature, and the thermal conductivity and thickness of coating, the concrete cover depth and the time of fire exposure have a significant effect. In addition, the internal steel bars have little effect on the temperature field of the section, due to the larger thermal conductivity. It can be assumed that the average temperature of steel bar is the same with the concrete at the same position. Therefore, the thermal conductivity ($\lambda_{co}$) and the coating thickness ($h_{co}$), the exposure time ($t_{fire}$) and the position of calculated point are the main factors for predicting section temperature in this paper.

2.1. FE model analysis

The FE software package ABAQUS was used to realize the proposed FE model. For simplifying the calculation, it is assumed that no heat source existed inside the structure, and the heat released by hydration can be ignored. Besides, all of the concrete, CFRP and fireproof coating were isotropic materials, with the same thermal properties in all directions.

During the thermal response analysis, the thermal properties at high temperature of concrete, fire coating and CFRP were obtained from Dong [7]. The increase of environment temperature followed the ISO834 standard fire curve. The concrete and fireproof coating materials were modeled with a 2-dimensional 4-node (DC2D4) heat transfer element. The element size was $5mm \times 5mm$. According to the suggestion given by Eurocode 2 [9], the convective heat transfer coefficient on the exposed surface was taken as $25 W/(m^2\cdot{^\circ}C)$; the comprehensive radiation coefficient was 0.8; the convective heat transfer coefficient on unexposed surface was taken as $9 W/(m^2\cdot{^\circ}C)$. For transient heat transfer analysis, “Tie” constraint mode was used to couple the temperature gradient of the coating or CFRP to the concrete material. In the thermal analysis, initial temperature $20 \degree C$ was given to each element and node of the model. The Stefan-Boltzman constant was $5.67\times10^{-8} W/(m^2\cdot{^\circ}C^4)$ and the absolute zero was $-273 \degree C$.

2.2. Validation of the FE model

In this section, CFRP-strengthened beam B2-1 in the literature [9] was simulated to verify the accuracy of the FE model in this paper. Beam B2-1 had a cross-section dimension of 250 mm width and 450 mm depth, with 20 mm thick fireproof coating at three-side of concrete beam. The thermal analysis results are shown in Fig.1. The comparison of numerical and test results are shown in Fig.2. The predicted curve shows a good agreement with the test data, which proves the FE model well in this paper.

2.3. Simplified calculation method

In this section, the relationship between influencing factors and beam section temperature was
investigated by using one-dimensional heat transfer FE method. After that, a series of calculation formulas, for predicting coating surface temperature, concrete surface and internal temperature, were presented and validated with numerical results. In order to eliminate the influence of the two unexposed sides, a cross-section of concrete beam with 1000 mm width and 450 mm depth was chosen to study the relationship between influencing factors and internal temperatures. The typical section temperature field distribution is shown in Fig.3. It can be seen that the temperature gradient distribution is nearly uniform along the width direction. In the following case study, the effects of four main factors were investigated to derive the simplified calculation method. The parameter change values are shown in Table 1.

Tabel 1. Changing range of parameters

| Parameters       | Changing Range   |
|------------------|------------------|
| $h_{co}$ (mm)    | 0, 10, 20, 30, 40, 50, 70 |
| $\lambda_{co}$ (W/(m²·℃)) | 0.06, 0.08, 0.10, 0.12, 0.14 |
| $t_{fire}$ (hour) | 0.5, 1.0, 1.5, 2.0, 2.5, 3.0 |
| $d$ (mm)         | 0, 20, 40, 60, 80, 100, 150, 200 |

Fig. 3 Temperature field distribution

2.3.1. Calculation for Coating Surface Temperature

In the thermal analysis, the convective heat transfer coefficient, the emissivity of coating surface and the standard fire curve were constant. It was found that the coating surface temperature was a function of only time of fire exposure. Fig.4 shows the temperature difference at coating surface between the simulated value from FE analysis and the calculated value from ISO834 fire curve. It shows that the temperature difference changes little after 30 min. For convenient, the coating surface temperature $T_{co}$ at any time can be calculated by the following formula.

$$T_{co} = 345 \log_{10} (8t_{fire} + 1) - \frac{220}{t_{fire}} + 10$$  \hspace{1cm} (1)

Where $t_{fire}$ is the time of fire exposure, min; $T_{co}$ is the coating surface temperature, °C.

2.3.2. Calculation for Concrete Surface Temperature.

The little effect of CFRP sheets on section temperature could be negligible. Thus, the temperature at the exposed surface was related to the time of fire exposure, the thickness and thermal conductivity of fireproof coating. The effect of these factors were investigated by FE method in the following section. Fig.5 shows the relationship between the temperatures at concrete surface with different thickness coating. The thermal conductivity of fireproof coating in the models were all $0.12W/(m²·℃)$. With the coating thickness increasing, the temperature at concrete surface decreases at any exposed moment. The change law is not obvious. Then the temperature data with different thickness coating were divided by the data with $h_{co}=0$ for normalization, as shown in Fig.6. The temperature decline is exponential form, and can be approximated by the following formula.
\begin{equation}
\ln(\frac{\Delta T}{\Delta T_0}) = k_1 \cdot t_{co}^k
\end{equation}

Where \( \Delta T_{co} \) is the temperature rise of the concrete beam surface at a certain time, °C; \( k_1, k_2 \) are two parameters calculated by formula (3) and (4):

\begin{align*}
k_1 &= 0.358 \tanh(0.6423 t_{fire}) - 0.5886 \\
k_2 &= 0.05 t_{fire} + 0.53
\end{align*}

Fig.5 shows as the thermal conductivity increases, the concrete surface temperature decreases gradually at any fire moment and the reduction amplitude is substantially linear. Liked the above section, the normalized data is shown in Fig.8, and the data can be unified into a straight line. The concrete surface temperature \( T_0 \) can be calculated by the following formula:

\begin{equation}
T_0 = k_1 (\Delta T_0' + 20)
\end{equation}

\begin{equation}
k_3 = 6.9 \lambda_{co} + 0.17
\end{equation}

Where \( \Delta T_0' (\lambda_{co} = 0.12 W/(m^2 \cdot \degree C)) \) is the concrete surface temperature difference at any moment, °C; \( k_3 \) is the parameter related to the coating thermal conductivity, can be given by equation (6).

\begin{align*}
\ln(\frac{\Delta T}{\Delta T_0}) &= k_4 \cdot d \\
\Delta T_0' &= T_0 - 20
\end{align*}

Where \( T_0 \) is the concrete beam internal temperature rise at any moment, °C; \( \Delta T_0' \) is the rise of surface temperature at a certain moment after correction, °C; \( d \) is the distance from internal node to beam surface faced fire, mm; \( k_4 \) is the parameter by formula (9).

\begin{align*}
k_4 &= 0.0443 \tanh(1.0152 t_{fire}) - 0.0586
\end{align*}
Finally, the internal node temperature can be calculated by the formula (10):

$$T_d = \Delta T_d + 20$$  \hspace{1cm} (10)

The distance from concrete surface (mm)

\begin{align*}
0 & \quad 20 & \quad 40 & \quad 60 & \quad 80 & \quad 100 & \quad 120 & \quad 140 & \quad 160 & \quad 180 & \quad 200 \\
0.0 & \quad 0.2 & \quad 0.4 & \quad 0.6 & \quad 0.8 & \quad 1.0
\end{align*}

The distance from concrete surface (mm)

\begin{align*}
0 & \quad 20 & \quad 40 & \quad 60 & \quad 80 & \quad 100 & \quad 120 & \quad 140 & \quad 160 & \quad 180 & \quad 200 \\
0.0 & \quad 0.2 & \quad 0.4 & \quad 0.6 & \quad 0.8 & \quad 1.0
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The distance from concrete surface (mm)

\begin{align*}
0 & \quad 20 & \quad 40 & \quad 60 & \quad 80 & \quad 100 & \quad 120 & \quad 140 & \quad 160 & \quad 180 & \quad 200 \\
0.0 & \quad 0.2 & \quad 0.4 & \quad 0.6 & \quad 0.8 & \quad 1.0
\end{align*}

(a) 0.5h, 1.5h, 2.5h of fire exposure

(b) 1h, 2h, 3h of fire exposure

Fig.9 Internal temperature versus time curve at distances from surface

3. Calculation of section temperature under three-side fire

In fact, the CFRP-strengthened RC beams are often exposed to three-side fire. The above FE models were used to obtain the relationship between the temperature at three-side fire condition and one-side fire condition. The specimen B2-1 in the literature [9] was simulated in this section as reference. Fig.10 shows the internal temperature at different locations within the beam section at thermal conductivity $\lambda_{co} = 0.12W/(m\cdot^\circ C)$. Through regression analysis, the better internal temperature under three-side fire condition can be calculated by a linear superposition of that under one-side fire, as formula (11). Fig.11 shows the comparison between the regression values by formula (7), (11) and the simulated values by FE model. It is found that the calculated values have a good agreement with the simulated values, so the presented simplified formula can greatly improve the computational efficiency.

$$T_d = \Delta T_{d,1} + \Delta T_{d,2} + \Delta T_{d,3} + 20$$  \hspace{1cm} (11)

Where, $\Delta T_{d,1}$, $\Delta T_{d,2}$, $\Delta T_{d,3}$ are the temperature rise under separated one-side condition, $^\circ C$.

(a) Location of calculated points (mm)

(b) With 30mm coating thickness

Fig.10 Internal temperature under three-side fire condition
4. Compared with the test data
In order to validate the simplified formulas given in this paper, the calculated values were compared with the tested values of specimen B2-1 in the literature [9]. As shown in Table 2, the ratio of calculated values to the test values is mostly from 0.884 to 1.254 at the six moments of fire exposure, which proves the simplified method an acceptable precision.

Table 2. Comparison between formula and test values (℃)

| Position     | Fire at 0.5h | Fire at 1.0h | Fire at 1.5h |
|--------------|--------------|--------------|--------------|
|               | Test | Formula | T/F | Test | Formula | T/F | Test | Formula | T/F |
| Beam surface  | 105.1 | 92.8   | 0.884 | 160.5 | 159.2 | 0.991 | 207.0 | 228.2 | 1.102 |
| Corner bar    | 52.4  | 51.3   | 0.979 | 106.3 | 117.8 | 1.111 | 155.0 | 187.5 | 1.210 |
| Middle bar    | 29.2  | 36.8   | 1.260 | 75.1  | 81.1  | 1.080 | 99.5  | 124.8 | 1.254 |

| Position     | Fire at 2.0h | Fire at 2.5h | Fire at 3.0h |
|--------------|--------------|--------------|--------------|
|               | Test | Formula | T/F | Test | Formula | T/F | Test | Formula | T/F |
| Beam surface  | 256.5 | 281    | 1.096 | 296.1 | 333.2 | 1.125 | 358.2 | 376.4 | 1.050 |
| Corner bar    | 214.2 | 233.8  | 1.093 | 236.0 | 293.5 | 1.244 | 296.3 | 336.1 | 1.134 |
| Middle bar    | 114.4 | 183.9  | 1.520 | 154.3 | 225.2 | 1.459 | 213.0 | 263.0 | 1.188 |

5. Conclusion
(1) The coating surface temperature decreases with the increase of the coating thickness and is only related to the ISO 834 standard fire curve. The concrete surface temperature decreased with the increase of coating thickness and increased linearly with the increase of thermal conductivity. The concrete internal temperature is only influenced by the temperature at the surface, the location from the surface and the time of fire exposure.

(2) Calculation method of beam internal temperature under single-fire is established. By giving the main influence factors such as fire exposure time, coating thickness and thermal conductivity, temperature at any node can be calculated. Through linear superposition, the internal temperature under the three-side fire condition can also be calculated with well precision.

(3) Temperature predicting method presented in this paper has a good match with FE simulated values and test values, avoiding complex calculation process. This paper provides a good method for fire design of CFRP-strengthened RC beams.

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