STUDY ON FLEXURAL BEHAVIOR OF FIRE-EXPOSED RC BEAMS STRENGTHENED WITH SMPM

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ABSTRACT :

Rehabilitation with SMPM (high-strength steel wire mesh and polymer mortar) is a new technique of structural strengthening. As a new technique of strengthening, it has a series of obvious advantages. Experiments were conducted to investigate the flexural behavior of 3 RC beams. BF-1 is a comparative beam which is not on fire, BFF-1 is a comparative one fire-exposed, and BFF-2 is a strengthened specimen after fire. The Experimental results showed that the flexural load-carrying capacity and stiffness of the fire-exposed RC beam were reduced. In the fire-exposed course, temperatures of steel and concrete were not measured. The temperature distribution of the beam is calculated by thermal analysis with ANSYS procedure. The flexural load-carrying capacity and stiffness of the strengthened beam were increased effectively. The effect of this rehabilitation can reach the level of RC beams before fire on load-carrying capacity. Based on the tests and analyses results, the design formulae of the flexural load-carrying capacity and stiffness were supposed. The calculated results are in good agreement with the experimental ones.

KEYWORDS: SMPM, Fire-exposed RC Beam, Flexural Strengthening, ANSYS, Thermal analysis

1. INTRODUCTION

Rehabilitation with SMPM is a new technique of structural strengthening. Compared to other strengthening methods, it has a series of obvious advantages (Yao *et al*, 2005). First, the strengthening structure and the original one bond and work together well. Second, the construction is simple and does not require large-scale execution machines and templates. Third, it has good durability, resistance to elevated temperatures and fireproof performance. Fourth, appearance and functions of the building are not affected. Last, pollution to the construction and the environment is little.

There have been a few studies on the behavior of RC beams strengthened with SMPM including beam flexural and shearing tests (Nie and Wang *et al*, 2005& Nie and Cai *et al*, 2005) by tsinghua university and fire resistance test of RC beam rehabilitated with SMPM (Wang *et al*, 2007) by china academy of building research.

2. EXPERIMENTAL PROGRAMMING

2.1. Design of The Specimens

Three RC specimens were designed and produced. The design strength of concrete is C20. Number and characteristics of the specimens are showed as Table 2.1. Dimensions of specimens and arrangement of reinforcement are showed as Fig. 1.

Table 2.1 Number and characteristics of the specimens

No.	Characteristic
BF-1	Comparative beam which is not on fire
BFF-1	Comparative one fire-exposed
BFF-2	Strengthened specimen after fire

After production and maintenance finished, BFF-1 and BFF-2 were on fire for 30 min. BFF-2 was rehabilitated with SMPM. Arrangement of the steel wire mesh is showed as Fig. 2.
The style of the high-strength steel is 6 × 7 + IWS with the tensile strength limit 1641 MPa, elasticity coefficient 1.34 × 105 MPa. The nominal diameter is 3.05 mm. Polymer mortar used in the experiment was mixed by polymer latex, cement and sand in a certain percentage.

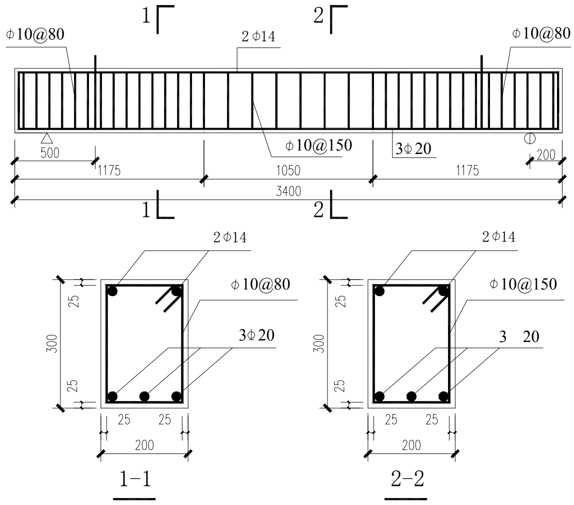

Fig. 1 Dimensions of specimens and arrangement of reinforcement

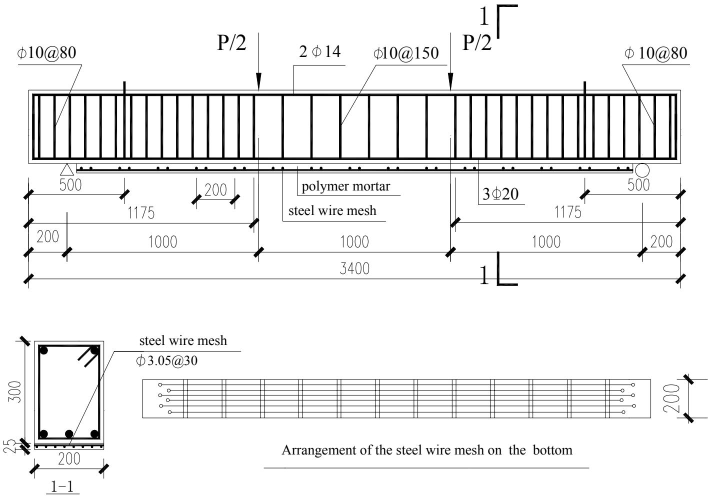

Fig. 2 Arrangement of the steel wire mesh

2.2 Fire-exposed Program of BFF-1 and BFF-2

Fire-exposed program of BFF-1 and BFF-2 was established based on article (Yao and Huang *et al,* 2007). The time on fire of the two beams was controlled in 30 min, and the ultimate maximum deflection should not overcome $l_0/150$. After the fire, deflections of the two beams were $l_0/214$ and $l_0/159$.

2.3 loading System

Calculation of load-carrying capacity referred to norms (GB 50010-2002) and the literature (Nie *et al,* 2005) .
Specimens were supported as Fig. 3, with the oil jack (60t) applying load on it through the cross-beam of allocation. The value of the load was measured and controlled by end instrument. Test setup is showed in Fig. 3, loading system referred to literature (Min *et al*, 1994).

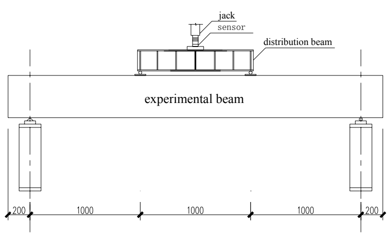

Fig. 3 Test setup

3. ANALYSIS OF THE EXPERIMENTAL PHENOMENON AND RESULTS

Table 3.1 Main load

No.	M_y (KN•m)	M_u (KN•m)	Δ_y(mm)	Δ_u (mm)
BF-1	92	95.48	18	41.82
BFF-1	86	87.05	21	43.64
BFF-2	92	94.33	19	43.49

Note: M_y -Measured yield moment; M_u -Measured limit moment;
Δ_y -The largest yield deflection in the mid-span; Δ_u -Measured largest ultimate deflection in the mid-span.

Table 3.2 Comparison of main load

Comparison group	α	β
BFF-1 、BFF-2	106.98%	108.36%
BF-1 、BFF-2	100%	98.80%

Note: α- Measured yield moment ratio of reinforced samples and the comparative one;
β- Measured limit moment ratio of reinforced samples and the comparative one.
Table 3.1 and 3.2 show the main results of the experiment based on the article (Yao, Huang *et al*, 2007).

4. ANALYSIS OF THE LOAD-CARRYING CAPACITY FORMULA

4.1 Load-carrying Capacity Loss of The Fire-exposed Beams

As thermocouples were not arranged on steel bars or in concrete in the experiment, it was difficult to estimate the intensity loss of the materials after the fire. Two methods were used in this paper to know the beams' temperatures of different sections. One of the methods was thermal analysis by ANSYS numerical simulation, the other one referred to the results of "Fire Resistance Test of RC Beam Retrofitted with Cover of High Strength Steel Mesh and Polymer Mortar".

4.1.1 Numerical simulation

ANSYS thermal analysis based on the principle of conservation of thermal energy balance equation. Temperature of each node and other physical parameters was calculated in finite element method. In this paper, a nonlinear thermal analysis was done to simulate the fire-exposed process by ANSYS.

In the analysis process, solid 70 and link 33 were used to simulate concrete and steel bars. The two kinds of elements are both thermal analysis elements. Concrete and steel bars shared nodes to ensure the transmission of temperature. According to the symmetry of the structure, half model was created.

(1) Material property of the steel bar in high temperature

1) Thermal conductivity of general structural steel based on the formula (ENV 1993-1-2 & ENV 1994-1-2) given by EC 3 and EC 4.

$$\lambda_s = \begin{cases} 54 - 3.33\times10^{-2} T_s & 20°C \le T_s \le 800°C \\ 27.3 & 800°C < T_s \le 1200°C \end{cases} \tag{4.1}$$

λ_s - Thermal conductivity of the steel, W/(m·℃);

T_s- Temperature of the steel.

2) Specific heat capacity of the general structural steel based on formula (BS 5950) in relative manual written by BSI.

$$C_s = 470 + 0.2T_s + 0.00038T_s^2 \qquad 20°C \le T_s \le 1000°C \tag{4.2}$$

C_s -Specific heat capacity of the steel, J/(kg·℃);

T_s -Temperature of the steel.

(2) Material properties of the concrete in high temperature

1) The thermal conductivity of concrete mainly depends on the values of its various compositions. The main factors include aggregate types, moisture content, and the concrete composition. Formula suggested by Lie and Denham (Lie T. T. and Denham E. M. A., 1993) was used in the numerical simulation process.

$$\lambda_c = \begin{cases} 1.355 & 0°C < T_c \le 293°C \\ -0.001241T_c + 1.7162 & T_c > 293°C \end{cases} \tag{4.3}$$

λ_c -Thermal conductivity of the concrete, W/(m·℃);

T_c-Temperature of the concrete.

2) Specific heat capacity of the concrete increases with the rising temperature. Numerical simulation based on the formula (ENV 1994-1-2) recommended by EC 4.

$$C_c = -4(T/120)^2 + 2T_c/3 + 900 \qquad 20°C \le T_c \le 1200°C \tag{4.4}$$

Cc- Specific heat capacity of the concrete, J/(kg·℃);

T_c - Temperature of the concrete.

Reinforced concrete beams were fired on three sides including one bottom and two flank sides. Temperature was imposed on the three sides according to the standard warming-up curve. Distribution of temperature after 30 min was shown in Figure 4. Steel-temperature in the bottom of mid-span over time is showed in Figure 5.

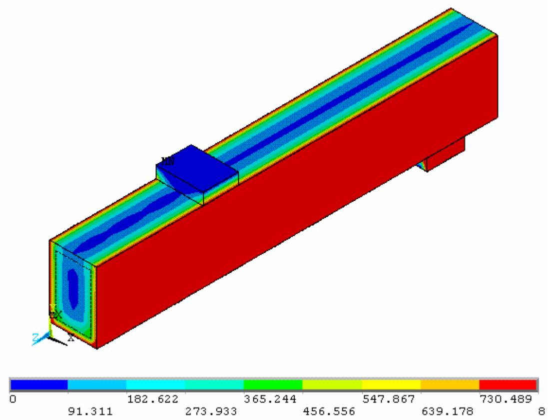

Fig. 4 Distribution of temperature after 30 min

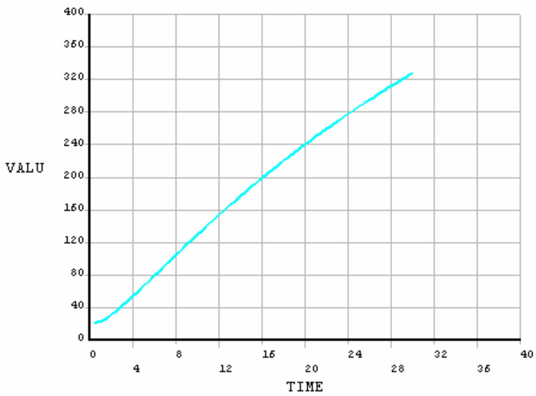

Fig. 5 Steel temperature curves at mid span

The analysis suggested that steel-temperature in the bottom of the beam was about 330 degrees after 30 minutes.

4.1.2 The results gotten from Fire Resistance Test of RC Beam Rehabilitated with high-strength steel wire mesh and polymer mortar

According to "Fire Resistance Test of RC Beam Rehabilitated with high-strength steel wire mesh and polymer mortar" (Wang *et al*, 2007), reinforced concrete beams were fired on three sides, and the temperature distribution of the steel bars were nearly the same as it of stirrup in the test. Stirrup temperature distribution versus time curve is showed in Fig. 6.

The test suggested that steel-temperature in the bottom of the beam was about 237.5 degrees after 30 minutes. Results of the thermal analysis by ANSYS and the test are close.

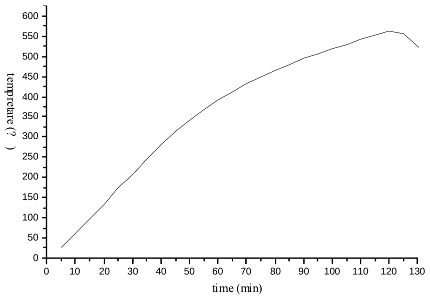

Fig. 6 Stirrup temperature distribution versus time curve

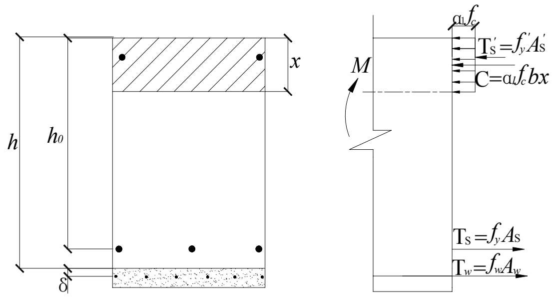

Fig.7 Calculating graph of flexural capacity

According to "Building Appraisal and Treatment after Fire" (Min *et al*, 1994), in the natural cooling conditions, the relationship of yield strength of steel and temperature is as follows.

$$\begin{cases} f_{yT_m}/f_y = 1.0 & T_m \le 330°C \\ f_{yT_m}/f_y = 1.1 - 3.0\times10^{-4}T_m & 330°C < T_m \le 600°C \end{cases} \tag{4.5}$$

f_{yT_m} - Yield strength of steel bar at T_m ;

f_y - Yield strength of steel bar at room-temperature;

T_m - Temperature of the steel bar.

According to the "Fire-resistant Design of Steel and Steel-concrete Structures" (Li *et al*, 2005), the compressive strength of concrete has just a small reduction under 400℃ but an obvious one when the temperature exceeds 400℃. The compressive strength of concrete when temperature exceeds 900℃ is less than one-tenth of it at the normal temperature.

Based on the comprehensive analysis of the above, only reduction of the concrete strength was considered in the two materials (concrete and steel). Considering the strength and elasticity coefficient decrease, section without the concrete protective layer was taken as the effective calculating one to calculate the load-carrying capacity of fire-exposed RC beam.

4.2 Calculation of load-carrying capacity of reinforcement beam

Calculation of load-carrying capacity of reinforcement beam took the method of Flexural strengthening RC Beams'.

$$\alpha_1 f_c bx + f_y' A_s' = f_y A_s + \psi_{rw} f_w A_w \, , \tag{4.6}$$

$$\psi_{rw} = \frac{0.8\varepsilon_{cu} h / x - \varepsilon_{cu}}{f_w / E_w} \, . \tag{4.7}$$

ψ_{rw} can be gotten from the two equations above. Then ψ_{rw} was amended by η as follow.

$$\eta = \alpha(0.85 - \psi_{rw}) \, . \tag{4.8}$$

α equals to 5. When ψ_{rw} is bigger than 0.65, it won't be amended. Then load-carrying capacity of fire-exposed RC beam can be calculated through the equations (4.9&4.10). Figure 7 can be referred.

$$\alpha_1 f_c bx + f_y' A_s' = f_y A_s + \eta \psi_{rw} f_w A_w \, ; \tag{4.9}$$

$$M = \alpha_1 f_c bx \cdot (h - x/2) + f_y' A_s' (h - \alpha_s') - f_y A_s (h - h_0) \, . \tag{4.10}$$

ψ_{rw} in the equation (4.9) was gotten from equations 4.6&4.7.

In the equations (4.9&4.10):

α_1-Coefficient, based on "concrete design specifications" (GB 50010-2002), α_1 equals to 1.0 when the degree of concrete is below C50;

f_c-Design value of concrete compressive strength in the direction of axis;

B, h-Effective breadth and height of the section;

x- Length of the compression area in the equivalent concrete rectangular stress graph;

f_y, f'_y-Tensile and compressive strength for design of ordinary steel;

A_s, A'_s-Tensile and compressive area-of-section of the steel;

f_w- Tensile strength for design of the steel wire;

A_w- Tensile area-of-section of the steel wire;

ε_{cu}-Ultimate compressive strain of the concrete, $\varepsilon_{cu} = 0.0033$;

E_s- Elasticity coefficient of the steel wire;

ψ_{rw}- Stress coefficient of the steel wire;

η- Amendment coefficient;

h_0- Effective height of the section before reinforcement;

M- The design value of bending moment after reinforcement.

Results in Table 4.1 were gotten by applying the real strength of the materials according to the formulas above.

Table 4.1 Comparison of the calculation and test results

No.	Test result M_u (KN•m)	Calculation result M (KN•m)	Calculation result/ Test result	Cracking behavior
BF-1	95.48	91.43	0.958	Concrete crushed after reinforcement had yield
BFF-1	87.05	88.67	1.018	Ibid
BFF-2	94.33	95.28	1.010	Ibid

The results suggest that calculation and test results are close. It is proper to use this calculation method.

5. CONCLUSIONS

(1) Compared to the fire-exposed beam without reinforce, working condition improvement of the strengthened fire-exposed beam was quite obvious. The strengthened fire-exposed beam can work well as the one not fired.
(2) ANSYS thermal analysis was applied to simulate the process on fire. The similar results show that the experimental results are proper.
(3) Formula results have a good agreement with the experimental data. The formula can provide basis to project in some extent.

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