NUMERICAL SIMULATION ON THE FIREPROOF BEHAVIOR OF RC BEAM STRENGTHENED WITH STRANDED MESH AND POLYMER MORTAR

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ABSTRACT :

The new strengthening technology by using high strength materials of stranded mesh and polymer mortar (SMPM) employs advantages in comparison with traditional ones, and present studies are mainly focusing on strength increasing of members. In this paper, numerical simulation on fireproof behavior of RC beam strengthened by SMPM is carried out with ABAQUS program, in which the coupled process of temperature and displacement is fully considered, and the real circumstance of fire exposing in a large stove is reproduced. The calculating formulas of thermal conductivity and specific heat capacity are proposed by analyzing the thermophysical characteristics of the polymer mortar. Variations in deflection at span center and section temperature of the strengthened beam under standard temperature-time curve is also simulated. Variation in section temperature of beam in calculation is closely matched to the test. Deflections of span center in both experiment and numerical simulation reach to 190mm when fire loading lasts 120min, which is below the maximum allowance limit regulated by Fireproof Code of Buildings (L/20, 255mm for the beam). Therefore, the new strengthening method can satisfy fireproof requirement no need to take any other measures.

KEYWORDS: Strengthening; Stranded Mesh and Polymer Mortar (SMPM); fireproof behavior; numerical simulation; conductivity coefficient; specific heat

1. INTRODUCTION

Strengthening with high strength materials of stranded mesh and polymer mortar (SMPM) is a new technology proposed by Korea first. In the past few years, the research and development of domestic material with independent intellectual property rights have been done by China Academy of Building Research (CABR). The technology has special advantages compared with other traditional ones, however, majority of present studies are focusing on strength increment of structure components and little on the other performance characteristics (Yue M.G. 2007, Yao Q.L. 2005 and Nie J.G. 2005). So in this paper a numerical simulation on the fireproof behavior of RC beam strengthened by SMPM is carried out with ABAQUS program on the basis of previous experiment (Wang Y.Y. 2007).

2. FINIT ELEMENT MODEL

2.1 Introduction of the Fireproof Experiment (Wang Y.Y. 2007**,** GB/T9978—1999 and GB 50045—95)

At the beginning, a brief introduction of the fireproof experiment is presented. A simply supported beam is designed with total length of 5.7m in experiment. The effective length of the beam in calculation is 5.1m and the cross-section is 200mm×350mm. The grade of concrete is C20 and the covering thickness is 25mm. The force bearing reinforcement at the beam bottom is 2⌀16 and the supporting rebar at the top is 2⌀10, and the stirrup arrangement is ϕ8@100/200. The beam is strengthened with stranded mesh and polymer mortar and the specification of stranded mesh is ϕ3.05@30, and the covering thickness of strand is about 13mm.

Four concentrated forces are applied at 1/8, 3/8, 5/8 and 7/8 of beam's length and the force value is gradually increased to 80% (10.5kN at each position) of the strengthened beam's bearing capacity by 5 steps. There shall be a 10min interval between each step. The fire load starts up when the dead load completely applied, and dead load should remain unchanged until the test end. The temperature of the stove shall accord with the standard temperature curve. The maximum deflection at span center reaches to 191.5mm while the fire loading lasts for 120min, which is below the maximum allowance limit regulated by Fireproof Code of Buildings L/20, that is, 255mm for the beam.

2.2 Establishing the Finite Element Model

According to the beam's parameters in experiment, the finite element model is established with ABAQUS procedure. The concrete and mortar are modeled in one part with solid element first of all and then material property is assigned to different portion. The reinforcing cage of the rebar and strand is modeled in another part with truss element. The next step is to combine the two together at proper position by the command 'embedded' which can simulate the sticking and slipping between concrete and reinforcement perfectly. The finite element model is established by now, see figure 1.

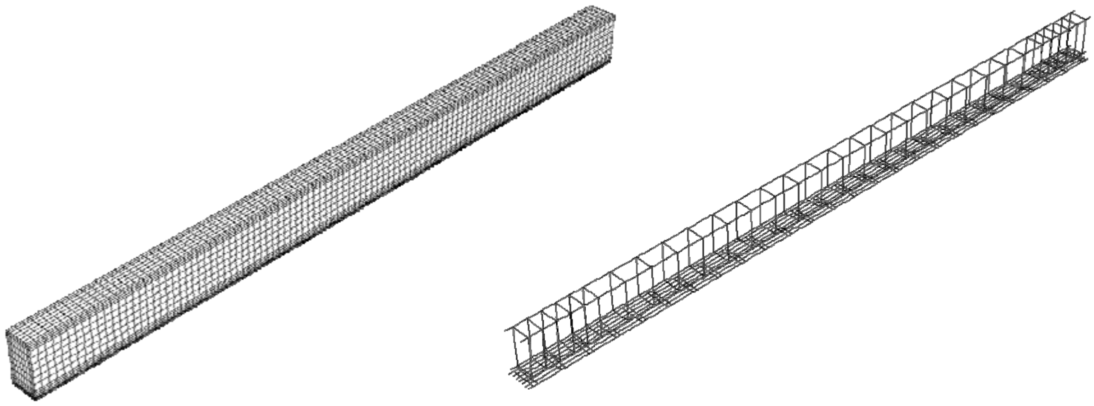


Fig. 1 Finite element model of RC beam

The load in simulation is consistent with the experiment that includes dead load and fire load. The loading process is divided into 3 steps, the first step gravity load of the beam added, the second step is the four concentrated forces, the initial value of which is set to very small in order to converge easily and then gradually increases to the preset value, in the finally step, fire load is applied according to the curve of standard temperature while the dead load remaining unchanged and the time of this step is 120min.

3. THERMOPHYSICAL AND THERMODYNAMICAL CHARACTERISTICS

The physical and dynamic characteristics of rebar, concrete and mortar may be changed under high temperature account for the variation in physical parameters. The fireproof characteristics of material can be reflected in two aspects: a) physical characteristics of material for the temperature field calculation of structure component, including thermal expansion coefficient, heat-transfer conductivity, specific heat and density etc. b) dynamic characteristics of material for the internal force and deflection calculation, and also for fireproof characteristic checking, including young's modulus, strength, constitutive relationship of strain and stress, strain relaxation and creeping etc. Compared with the other parameters, the expansion coefficient and density of the material have little sensitivity to temperature and small affection to temperature stress, so they are neglected in numerical simulation. In addition, only taking short-term fire loading into consideration, therefore the affection of strain relaxation and creeping of reinforcement are also neglected. The variation rule of material characteristic of strand at high temperature is approximately considered the same as reinforcement.

3.1 Characteristics of Reinforcement and Strand at High Temperature

a) Heat-transfer conductivity of general steel is according to EC3 (1993) and EC4 (1994):

$$\lambda_s = \begin{cases} 54 - 3.33\times 10^{-2} T_s & 20°C \le T_s \le 800°C \\ 27.3 & 800°C < T_s \le 1200°C \end{cases} \quad (3.1)$$

λ_s refers to heat-transfer conductivity of steel (W/(m·℃)) and T_s refers to steel temperature.
b) The exact formula for specific heat calculation in manuals compiled by BSI (1990) is adopted in this simulation:

$$C_s = 470 + 0.2T_s + 0.00038T_s^2 \qquad 20°C \le T_s \le 1000°C \quad (3.2)$$

C_s refers to specific heat of general steel (J/(kg·℃)) and T_s refers to temperature.
c) The reduction factors of young's modulus and strength of general structure steel at high temperature are presented in table 1 and 2 according to EC3 (1993):

Table 1 Young's modulus reduction factors of structure steel at high temperature (E_T/E)

Temperature (℃)	20	100	200	300	400	500	600	700	800	900	1000	1100
Coefficient	1.000	1.000	0.900	0.800	0.700	0.600	0.310	0.130	0.090	0.068	0.045	0.023

Table 2 Material strength reduction factor of structure steel at high temperature (f_{yT}/f_y)

Temperature (℃)		20	100	200	300	400	500	600	700	800	900	1000	1100
Total Strain	0.00	1.000	1.000	0.807	0.613	0.420	0.360	0.180	0.075	0.050	0.038	0.025	0.055
	0.02	1.000	1.000	1.000	1.000	1.000	0.780	0.470	0.230	0.110	0.060	0.050	0.030
	0.15	1.000	1.000	1.000	1.000	1.000	0.780	0.470	0.230	0.110	0.060	0.050	0.030

3.2 Characteristics of Concrete at High Temperature

A series of physical and chemical variations in concrete component will happen at high temperature and may affect the characteristic of concrete. Some researches indicate that concrete may shrink and the skeletal material may expand as portion free water and gel water evaporate when temperature below 300℃; when temperature reaches to 400℃, the gel of C-S-H becomes loose and some $Ca(OH)_2$ start decompose; when temperature reaches to 500℃, the concrete has been dehydrated completely, the concrete slurry shrinks sharply and skeletal material expands continuously, so large internal stress may generate and the sticking surface inside may be damaged, at the same time, a great deal of $Ca(OH)_2$ begins to decompose; when temperature reaches to 700℃, the concrete becomes residual material with loosen structure, and the crack between skeletal material and slurry develops quickly; when temperature reaches to 900℃, the limestone starts decompose, skeletal material and slurry disjointed completely (Lin W.M. 1996, Wu B. 1999).
a) The hear-transfer conductivity of concrete mainly depends on its components, the key affection factors including type of skeletal material, moisture content and mixture ratio of concrete etc. In simulation, the formula proposed by Lie and Denham (1993) is adopted:

$$\lambda_c = \begin{cases} 1.355 & 0°C < T_c \le 293°C \\ -0.001241T_c + 1.7162 & T_c > 293°C \end{cases} \quad (3.3)$$

λ_c is heat-transfer conductivity of concrete (W/(m·℃)) and T_c is the concrete temperature.

b) The specific heat of concrete will increase with temperature and the following formula is suggested by EC4:

$$C_c = -4(T/120)^2 + 2T_c/3 + 900 \qquad 20°C \le T_c \le 1200°C \qquad (3.4)$$

C_c is specific heat of concrete (J/(kg·℃)) and T_c is concrete temperature.
c) Variation in young's modulus and strength of concrete under high temperature are proposed in research of Guo Zhenhai and Li Wei (1991):

$$E_{c,T} / E_c = -0.0011T_c + 0.83 \qquad 60°C \le T_c \le 700°C \qquad (3.5)$$

$$f_{cu,T} / f_{cu} = 1/(2.4 \times (T_c - 20)^2 \times 10^{-17} + 1) \qquad 20°C \le T_c \le 1000°C \qquad (3.6)$$

$$f_{t,T} / f_t = 0.001T_c + 1 \qquad 20°C \le T_c \le 1000°C \qquad (3.7)$$

$E_{c,T}$、E_c denote the concrete young's modulus at high temperature and normal temperature respectively; $f_{cu,T}$、f_{cu} denote the compressive stress of cubic test block at high temperature and normal temperature; $f_{t,T}$、f_t denote the tensile stress of cubic test block at high temperature and normal temperature.

3.3 Characteristics of Polymer Mortar under High Temperature

The polymer mortar used in strengthening is a new material, the latex in mortar mixing is a water material without any organic solvent, so it has perfect sticking and fireproof characteristics, however, there is no research on its fireproof characteristic at high temperature by now. In this paper, based on the variation in concrete characteristic at high temperature and the numerical simulation of variation in temperature of polymer mortar, the calculation formulas of hear-transfer conductivity and specific heat of polymer mortar are proposed (Eqn. 3.8 and Eqn. 3.9). Compared with concrete, the polymer mortar has smaller heat-transfer conductivity and larger specific heat, so the fireproof characteristic of polymer mortar is better than concrete. As the strengthening layer generally lies in tension area, the tension strength of mortar has little affection on force bearing capacity of structure component, therefore the variations in young's modulus, tension strength and compression strength of polymer mortar under high temperature are assumed identical to concrete.

$$\lambda_M = \begin{cases} 1.2873 & 0°C < T_M \le 293°C \\ -0.001179T_M + 1.6304 & T_M > 293°C \end{cases} \qquad (3.8)$$

$$C_M = -6(T_M/120)^2 + T_M + 1350 \qquad 20°C \le T_M \le 1200°C \qquad (3.9)$$

The meaning of parameters in above formulas is the same as concrete.

4. COMPARISON BETWEEN SIMULATION AND EXPERIMENT

The temperature distribution of the strengthened beam with 3 sides exposed to fire for 120min is displayed in figure 2. From which we can also clearly see the cross-section mesh, the outer 2-layer meshes of the beam are the cover of reinforcement except bottom side. At bottom, the first 3-layer meshes are strengthening layer in which the outer 2 layers of mesh is the cover of strand, and the upward 2-layer meshes from strengthening layer are the cover of reinforcement. From the temperature distribution, we can conclude: a) the cover of reinforcement is a perfect fireproof layer, in which the temperature decreases sharply from 1029℃ to about 580℃; b) the temperature gradient in strengthening layer is larger than in reinforcement cover, so the polymer mortar is better in fireproof.
The comparison between simulation and experiment is shown in figure 3, including temperature of stirrup at middle of lateral side, temperature of the center strand and deflection at span center. The dashed lines indicate

experiment value and the solid lines denote simulation value.

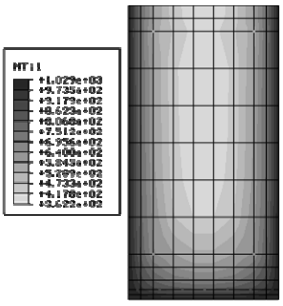
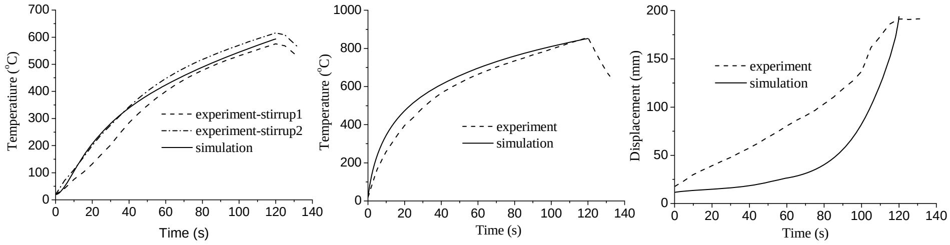


Fig. 2 Temperature distribution at 120min



a) Stirrup's temperature at middle of lateral side

b) Temperature of the central strand

c) Deflection at span center

Fig. 3 Comparison between numerical simulation and experiment

In fig. 3 a) and b), the temperature variation of reinforcement and strand in numerical simulation well agrees with which in experiment, therefore the procedure of ABAQUS can perfectly simulate the inner temperature distribution of RC member exposed to fire, in addition, the validity of formulas in thermophysical calculation of polymer mortar, which proposed in this paper, is approved by the strand temperature comparison. Large differences of variation in deflection at span center displayed nearly all through the process except at the beginning and end. In experiment, deflection increment of beam is nearly linear and slower in the former 100min while which is also linear but faster in 100-120min. In numerical simulation, the deflection remains nonlinear all through the process, and increment is slower in 80-120min compared with experiment. The total deflection of beam at span center is 193.8mm for simulation, which approaches to experiment (191.5mm). Deflection in both simulation and experiment are below the maximum allowance limit regulated by Fireproof Code of Buildings L/20 (255mm). Therefore, the new strengthening method can satisfy the fireproof requirement without taking any other measures (GB/T9978—1999 and GB 50045—95).

Now we will analyze the causes for difference of deflection in experiment and simulation. Figure 13 a) indicates the temperature of reinforcement approach to 500℃ at 80min, at the time, the burnt depth of concrete is not exceed the thickness of reinforcement cover, so the stiffness reduction of beam cross-section is little. On the other hand, the reduction in reinforcement yielding strength is also not much, about 0.8 times of which at normal temperature. As a result, the large displacement of 130mm at 80min is impossible. The previous researches indicate the deflection at span center of simply supported beam is affected by many factors, such as thickness of reinforcement cover, dead load in fire, size of member's cross-section. So the difference between experiment and simulation mostly caused by construction error, inaccuracy control of oil pressure (control manually in experiment) and measurement error while all the factors of simulation are in perfect state. So the fireproof characteristic of strengthened beam in real project may between the experiment and numerical simulation.

5. CONCLUSION

As to the new technology that strengthened with SMPM, most studies focus on the bearing capacity by now. However, the appraisement of a strengthening method not only on bearing capacity but also extensively on fireproof, mitigate corrosion, durability and environment protection etc. Therefore, based on the fireproof experiment of beam strengthened with SMPM, numerical simulation with ABAQUS procedure is carried out in this paper, summed up the above analysis, we can conclude:

- The variation in temperature of strengthened beam exposed to fire can be simulated perfectly by ABAQUS procedure, which can vividly reproduce the whole process of beam in fire;
- Formulas in calculation of heat-transfer conductivity and specific heat of the new polymer mortar are proposed by the comparison between numerical simulation and experiment;
- Both the simulation and experiment indicate the new technique strengthened with SMPM can satisfy the fireproof requirement without taking any other measures in addition other advantages, such as increasing member's strength obviously, convenient construction, small strengthening quantity and environment

protection.

The coupling of temperature filed and displacement field can be modeled by ABAQUS procedure perfectly. The numerical simulation can not only reduce the number of test member and save the cost but also offset the deficiency in experiment.

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