Finite Element Analysis of Bond Slip Constitutive Model of FRP Reinforced Concrete

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Abstract: ABAQUS has strong nonlinear analysis ability, so the numerical analysis of bond slip constitutive relation between FRP bars and concrete has been carried out with ABAQUS. By comparing the results of numerical calculation of different constitutive model, the constitutive relation of plastic reinforcement and concrete is obtained, and the suitable constitutive model is chosen, which provides the basis for the study of the structure selection in future, and it can also provide reliable numerical results for the future real experiments.

Keywords: Finite element analysis; FRP tendons; constitutive model; comparison; numerical calculation.

1. Introduction

Reinforced concrete such material has been widely used in many fields such as roads, bridges and buildings since its birth. The concrete has the characteristics of strong resistance to compression, and a relatively poor tensile strength. When these two kinds of materials are combined together to form a good tensile properties and compression performance, the mechanical properties and safety of concrete structures are greatly improved. With the widely application of reinforced concrete, some of the problems are gradually exposed, and the most common and difficult problem to solve is the corrosion of steel, especially in the bridge and port of these basic building. Steel bar will be corrosive by some corrosive medium (acid, alkali), and its ductility, strength and other aspects of the performance has different degrees of decline, will eventually lead to the failure of concrete structure. In order to solve this problem, some scholars began to study the fiber reinforced plastic (FRP), used to replace the reinforced concrete structure of the steel[1]. The tensile strength of FRP is higher than steel bar, and many other advantages, such as acid, alkali, anti magnetic, etc.. However, whether the FRP tendons and concrete can work effectively under the action of external force, it also determined by the bond slip relationship between them, which is a whole embodiment of the interaction mechanism between the two materials. After many years of research, the domestic and foreign scholars put forward a variety of FRP tendons and concrete bond slip constitutive models. In order to contrast what kind of model can more realistically reflect the relationship of bond slip between FRP tendons and concrete, and the numerical analysis is using the ABAQUS, chooses the suitable for FRP reinforced concrete beams, the bond slip constitutive and for the performance of FRP reinforced concrete beams in bending analysis provides the basis.

2. The constitutive model of bond slip between FRP bars and concrete

2.1 Constitutive model

2.1.1 BEP correction model

The BEP model was originally proposed by Popov et al. and used to describe the bond slip relationship between steel and concrete. Based on the characteristics of the reinforcement and FRP tendons, the BEP model is modified by Faoro et al.. The $\tau - S$ expression of the modified FRP bars and concrete is: [2]

- Ascending stage: $\tau = \left( \frac{S}{S_1} \right) ^{\alpha} , s \leq s_1$;  
- Horizontal section: $\tau = \tau_1, s_1 < s < s_2$;  
- Fall section: $\tau = \tau_1 - \frac{\tau_1 - \tau_2}{s_2 - s_1} (s_2 - s)$, $s_2 < s < s_3$;  
- Residual stress stage: $\tau = \tau_3, s > s_3$.

Where, $\tau_1$ is ultimate bond strength, $s_1$ is the slippage of $\tau_1$, $s_2$ and $s_3$ are the experiment measured
slippage, $\tau_3$ is residual stress. $\alpha$ is curve correction coefficient, and $\alpha < 1$.

2.1.2 Improved BEP model[3]

After a lot of experiments, Cosenza and other scholars put forward the improved BEP model in 1995, that the bond slip between FRP tendons and concrete is not in the horizontal phase ($\tau$ the same as $S$ continues to increase), so removed the horizontal section, the expression is as follows:

**Ascending stage:**

$$\frac{\tau}{\tau_1} = \left(\frac{S}{s_1}\right)^{\alpha}, s \leq s_1$$

**(5)**

**Fall section:**

$$\frac{\tau}{\tau_1} = 1 - p\left(\frac{S}{s_1} - 1\right), s_1 < s < s_3$$

**(6)**

**Residual stress stage:**

$$\tau = \tau_3, s > s_3$$

**(7)**

Where, $\alpha, p$ are corrected parameters. The parameters of the modified BPE model can be obtained by the test, and $\alpha$ is the area of A curve on the bottom.

2.1.3 Malvar model[4]

Malvar model is the bond slip constitutive relation of GFRP Bars and Neurosurgery. Malvar was obtained by considering the shape of different FRP bars on the basis of a large number of bond slip experiments, its expression is:

$$\tau = F\left(\frac{s}{s_m}\right) + (G - 1)\left(\frac{s}{s_m}\right)^2$$

$$1 + (F - 2)\left(\frac{s}{s_m}\right) + G\left(\frac{s}{s_m}\right)^2$$

**Expression**

$$s_m = D + E\sigma$$

**(8)**

2.1.4 Continuity model — Gao Danying[5]

The professor of Zhengzhou university Gao Danying continuity in put forward on the basis of summing up predecessors' experience of FRP tendons concrete bond-slip constitutive model. This model is more practical than the previous model, and the parameters are relatively small, which can express the relationship between FRP and concrete.

Expressions are as follows:

**Ascending stage:**

$$\tau = 2\tau_1\sqrt{\frac{s}{s_0}} - s/s_0, (0 \leq s \leq s_0)$$

**(10)**

**Fall section:**

$$\tau = \tau_0 + \tau_s + \tau_u, (s_0 \leq s \leq s_u)$$

**(11)**

Where, $\tau_0, s_0, \tau_s, \tau_u$, respectively, peak shear stress, the corresponding slip, residual shear stress and the corresponding residual slip value.

2.1.5 Zhang Haixia model[6]

The experimental method of single-ended drawing of FRP reinforced concrete members can be more accurate and the relationship between FRP tendons and concrete, and can obtain many valuable experimental data. Zhang Haixia was carried out on 84 FRP reinforced concrete specimens. The $\tau$-$s$ model was put forward through the concrete analysis of the results. Expressions are as follows:

**Ascending stage:**

$$\tau = \tau_s\left(M_1\frac{s}{s_u} + M_2\left(\frac{s}{s_u}\right)^2\right), (0 < s < s_u)$$

**(12)**

**Fall section:**

$$\tau = \frac{s}{N_1s - N_2}, (s_u < s < s_f)$$

**(13)**

**The residual phase:**

$$\tau = \tau_r, (s > s_r)$$

**(14)**
Where, \( M_1 = 2 \), \( M_2 = -1 \), \( \tau_r = 10 \) (mpa), \( \tau_u = 14 \) (mpa),

\[
N_1 = \frac{s_u \tau_r - s_r \tau_u}{s_u \tau_r (s_u - s_r)} , \quad N_2 = \frac{s_u - s_r \tau_r}{s_u \tau_r (s_u - s_r)}.
\]

(15)

### 2.2 Numerical simulation

The numerical example of this article is FRP reinforced concrete beam [Xu Xinsheng] [7], length is 1900mm, wide is 180mm, high is 250mm, adopts C30 concrete, the cube compressive strength is \( f_u = 30.1 \) MPa, two 14 mm compression reinforced at the top of the beam, elastic modulus is \( E = 200 \) Gpa, Resistance tensile strength is \( f_u = 380 \) Mpa, Poisson's ratio is \( \mu = 0.3 \), three diameter is 9.5 mm FRP tensile reinforcement at the bottom of the beam, elastic modulus \( E = 72 \) Gpa, Poisson's ratio is \( \mu = 0.23 \), diameter of the stirrup is 10mm, tensile strength \( f_u = 308 \) Mpa. When modeling using ABAQUS, use concrete constitutive according to specification taking 【《Code for design of concrete structures》GB 50010—2010】. Set nonlinear spring between FRP tendons and concrete, use it to simulate the bond-slip relationship between them. Applied concentrated load after the beam model is built. And compared the load displacement curves of numerical calculation with the experimental results. The beam model as shown in Figure 1.

![Figure 1. Spring detail drawing](image)

BEP \( \tau - s \) model was used to calculate figure 2. The improved BEP \( \tau - s \) model is used to figure 3.

![Figure 2. The BEP \( \tau - s \) model](image) ![Figure 3. The improved BEP \( \tau - s \) model](image)

The calculation of Figure 4 using Gao Danying \( \tau - s \) model. The Zhang Haixia \( \tau - s \) model was used to calculate figure 5.

![Figure 4. The Gao Danying \( \tau - s \) model](image) ![Figure 5. The Zhang Haixia \( \tau - s \) model](image)
By comparing the numerical results of different bond slip constitutive relation, the results show that the relationship $\tau - S$ can reflect the slip relationship between FRP bars and concrete. In the Gao Danying model and Zhang Haixia model of are relatively uniform, which shows that these two models are more realistic in the bond slip between the concrete and the concrete. In a few graphs, the bearing capacity of the concrete beam in the model beam is relatively large relative to the experimental beam, which is related to the position and quantity of the nonlinear spring. After the bottom of the concrete cracked, the tensile strength of the concrete is directly borne by FRP, and the bearing capacity of the beam is also influenced by the interaction of tensile reinforcement and concrete in ABAQUS. In the experiment of FRP reinforced concrete beam, the tensile FRP bar is to be anchored at both ends of the beam, and the length of anchorage is determined according to the experimental conditions. This makes as much as possible to consider the location and number of the nonlinear spring, so as to simulate the experimental process more real.

Although the results of numerical calculation and the experimental have some errors, but it has been able to correctly reflect the relative slip relationship between FRP bars and concrete, the above mentioned several constitutive models can be used in theory. In the curve is smooth and continuous, appearance is simple and clear, convenient use, Gao Danying model and Zhang Haixia model has relatively large advantage. This two models can be relatively objective reflect the real situation just only required to identify a few simple parameters. The former several model parameters is relatively more and need in the through bond slip curve for many times of matching to infer, and itself has some errors, by fitting the obtained data to calculate the shear force and relative slip will cause greater error.

3. Conclusion

The method of setting up a nonlinear spring in ABAQUS is feasible and can be used to simulate the relative bond slip between FRP bars and concrete. These constitutive relations are able to correctly reflect the bond slip relationship between fiber reinforced plastic reinforcement and concrete. Based on the principle of comparison results of $\tau - s$ curves and the upward trend of the curve and the uniformity of the curve, the method is simple and easy to implement in the finite element. The Gao Danying constitutive model and the Zhang Haixia constitutive model have the relatively large advantages.

4. References