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Calculation on uniaxial compressive strength of high strength concrete after wrapped by FRP

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Abstract: A theoretical calculation method of the axial compressive strength of a high strength concrete with fibre reinforced plastics (FRP) constraint is proposed. It is shown by test verification that the FRP strength devotion factor used for this method is in accord with actual conditions. FRP is not up to the ultimate strength when the concrete reaches the ultimate strength, whose strength devotion factor is in the range of 0.28 to 0.59, which is related to an elastic modulus. The method can be used to estimate axial compressive strength of the concrete strengthened with FRP. The theoretical strength is 10% to 30% higher than the measured one. The deviation comes mainly from a non-ideal bonding condition of FRP-concrete interfaces and discrete property of the testing data of compressive strength.

Key words: strengthening; high-strength concrete; fibre reinforced plastics (FRP); axial compressive strength; theoretical calculation

Some people[1-3] have studied the relationships among the improvement efficiency of the compressive strength of concrete wrapped by fibre reinforced plastics(FRP), the wrapping direction of continuous fibres, the thickness of FRP and the dimension of the concrete specimen. Their results showed that when the cross-section of the concrete was kept the same, the compressive strength of FRP wrapping concrete would increase with the increasing of the fibre skein's thickness, while the improvement efficiency would decrease. When the thickness of FRP skein was kept the same, the smaller the dimension of the concrete cross-section, the higher improvement efficiency. Their research was mainly on common strength concrete, rather than on high strength concrete. Some other people have studied the relationship between stress and strain of FRP wrapping concrete[4,5]. Zhang, et al. [6] have developed some theory models about FRP wrapping concrete. And Toutanji[7] studied the durability of FRP wrapping concrete structures. While in this paper, a calculation method on the uniaxial compressive strength of FRP wrapping concrete was inducted; the calculated results were also compared with the experimental results.

1 Mechanism Analysis of FRP Wrapping Concrete

When a concrete cylinder only sustains an axial load, without transversal constraint, there will exist a transversal tensile strain caused by the axial compression. This tensile strain contributes to the internal tensile stress. When the axial compressive stress of concrete reaches a critical value, some transversal cracks appear, thus the concrete cylinder will be restrained by FRP and the propagation of internal micro-cracks will also be restrained. This can keep the concrete microstructure continuous under higher axial compressive loads. So the compressive loading carry capacity is improved in this way.

In order to better understand the characteristics of FRP wrapping concrete, it is necessary to compare the FRP wrapping concrete with steel pipe concrete. Their differences are described as follows:

1) FRP is a kind of linear elastic material while the steel displays elasto-plasticity. When the lateral constraining force of concrete reached the yield force of steel, the restraining force of steel pipe exerting on the concrete was initiative. This force would remain the same during the whole loading process. When the concrete was wrapped by FRP, the lateral constraining force would change with the variant of lateral strain.

2) In the preliminary stage of loading, the lateral strain of steel was higher than that of concrete because the Poisson's ratio of steel was higher than that of concrete. Therefore, the steel could not restrain the concrete. But the FRP always had constraint to concrete because its Poisson's ratio was much lower than concrete's.

In the preliminary stage of loading, the

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deformation of concrete was larger than that of FRP skein. This made the FRP and concrete push each other, thus the restraining stress p came out. The preliminary restraining stress would retard the appearance of the longitudinal crack of concrete. With the increasing of axial load N, the longitudinal crack of concrete came out and the increment of lateral strain became larger. The push between the FRP and concrete was aggravated. And the lateral restraining force increased. This restraining force could make the micro-crack close again. So the compressive strength of concrete was increased. When the axial loading continued increasing, the concrete cylinder was destroyed, and the adhesive bond was also destroyed. The lateral strain of the concrete cylinder decreased slowly because of the constraint of FRP. During the whole process of loading, the concrete suffered three-dimensional compression, while the FRP skein suffered longitudinal compression and latitude tension. The longitudinal compression of FRP was so low that it could be neglected.

2 Deduction of Calculation Equation

Early studies have shown that, when the concrete cylinder only sustains an axial load, without transversal constraint, the relationship of the ultimate compressive stress of concrete and the restrained stress caused by wrapping can be expressed as

$$f'_c = f_c + k_1 p \tag{1}$$

where f'_c is the ultimate compressive stress of the wrapped concrete, f_c is the uniaxial compressive strength of plain concrete without wrapping, p is the lateral restrained stress caused by FRP wrapping, and k_1 is the influence coefficient of the lateral restraint on the uniaxial compressive strength of the wrapped concrete.

Priestley has drawn the conclusion:

$$f'_c = f_c\left(-1.254 + 2.254\sqrt{1 + 7.94\frac{p}{f_c}} - 2\frac{p}{f_c}\right) \tag{2}$$

Rewriting Eq.(2), k_1 can be expressed as

$$k_1 = -2.254 + 2.254\sqrt{7.94\frac{f_c}{p} + \frac{f_c^2}{p^2}} - 2 \tag{3}$$

If p is known, f'_c can be calculated. Here the p value is up to the concrete's transversal strain.

Here, the situation of concrete cylinder is discussed. In this discussion, there are three assumptions as follows:

1) p is distributed homogeneously on the whole interface of concrete.

2) The relative slippage between the FRP and the concrete is neglected.

3) Conform to the other hypotheses in mechanics of materials.

According to experimental observation, the situation for concrete prisms is contradictory to the above assumptions because of the stress concentration at FRP edges. But for concrete cylinder, the stress in FRP is below its ultimate tensile strength when the concrete cylinder is destroyed. So FRP's ultimate tensile strength cannot be used to calculate the concrete's restraining stress. Therefore, it is necessary to introduce a utilization coefficient of FRP's tensile strength k. k can be expressed as $k = \varepsilon_f / \varepsilon_{ful}$ (ε_{ful} is the ultimate strain of FRP, and ε_f is the strain of FRP while the concrete stress reaches the ultimate stress). The calculation model is shown in Fig.1.

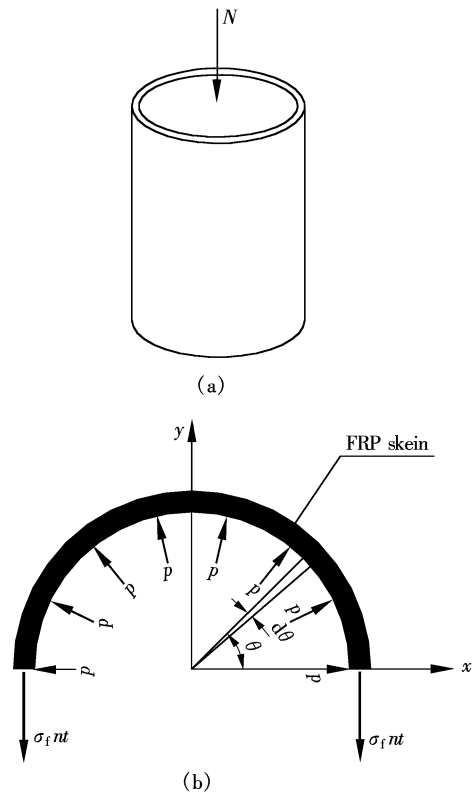

Fig.1 Calculation model. (a) The force applied on the concrete wrapped by FRP; (b) The force applied on the FRP skein

The balance equation of axial y direction can be obtained as follows according to Fig.1(b).

$$\int_0^{\pi} p\sin\theta R \mathrm{d}\theta = 2\sigma_f nt$$

$$p = \frac{2\sigma_f nt}{D} \tag{4}$$

where R, D are the radius and the diameter of cylinder; σ_f is the tensile stress of FRP when the external force of concrete cylinder reaches the ultimate load; n, t are the number of layers of FRP and the thickness of a single layer of FRP.

$$k = \frac{\varepsilon_{\text{f}}}{\varepsilon_{\text{ful}}}$$

$$\sigma_{\text{f}} = k\sigma_{\text{ful}} \tag{5}$$

where σ_{ful} is the the ultimate tensile strength of FRP.

Replacing σ_{f} and p with Eqs.(4) and (5) in Eq.(2), we obtain

$$f_{\text{c}}' = f_{\text{c}}\left(-1.254 + 2.254\sqrt{1 + 7.94\frac{2k\sigma_{\text{ful}}nt/D}{f_{\text{c}}}} - 2\frac{2k\sigma_{\text{ful}}nt/D}{f_{\text{c}}}\right) \tag{6}$$

It can be seen from assumption (1):

$$\varepsilon_{\text{f}} = v_{\text{cc}}\varepsilon_{\text{cc}} \tag{7}$$

where v_{cc} is the transversal deformation coefficient of concrete cylinder at ultimate load (vertical to loading direction), and ε_{cc} is the axial ultimate strain of concrete cylinder(parallel to loading direction).

To the mono-axial loading of concrete cylinder, when $\sigma = (0.9 - 1)\sigma_{\text{c}}$($\sigma_{\text{c}}$ is the cylinder's compressive strength), the volume strain of concrete was zero[8].

$$\Delta V_{\text{c}} = 0$$

$$\Delta V_{\text{c}} = \Delta\pi R^2 h = 2\pi Rh\Delta R + \pi R^2\Delta h = 0$$

$$\frac{\Delta h}{h} = 2\frac{\Delta R}{R}$$

$$\varepsilon_{\text{f}} = 0.5\varepsilon_{\text{cc}}$$

$$\varepsilon_{\text{cc}} = 2\varepsilon_{\text{f}} = 2k\varepsilon_{\text{ful}} \tag{8}$$

Mander, et al. [4] have pointed out

$$\varepsilon_{\text{cc}} = \varepsilon_{\text{co}}\left[1 + 5\left(\frac{f_{\text{c}}'}{f_{\text{c}}} - 1\right)\right] \tag{9}$$

Combined with Eqs. (8) and (9), the utilization coefficient of FRP can be obtained as follows:

$$2k\varepsilon_{\text{ful}} = \varepsilon_{\text{co}}\left[1 + 5\left(\frac{f_{\text{c}}'}{f_{\text{c}}} - 1\right)\right] = \varepsilon_{\text{co}}\left[1 + 5\left(-2.254 + 2.254\sqrt{1 + 7.94\frac{2k\sigma_{\text{ful}}nt/D}{f_{\text{c}}}} - 2\frac{2k\sigma_{\text{ful}}nt/D}{f_{\text{c}}}\right)\right] \tag{10}$$

k in Eq.(10) can be calculated by the dichotomy method in numerical analysis. f_{c}' can be obtained after substituting k in Eq.(6).

3 Comparison between Calculated Results and Experimental Results

The uniaxial compressive strengths of nine FRP wrapping concrete cylinders were tested. The detailed experimental process can be referred to in Ref.[9]. These cylinders were wrapped by one layer of CFRP, two layers of CFRP or three layers of GFRP, respectively. The properties of CFRP and GFRP are shown in Tab. 1. The comparison between the calculated results and the experimental results is shown in Tab.2.

Tab.1 Properties of CFRP and GFRP

Kinds	Thickness (single layer)/mm	Ultimate strain/%	Ultimate tensile strength/MPa
CFRP	0.7	1.5	890
GFRP	1.1	3.0	276

Tab.2 Comparison between calculated results and experimental results

Sample mark	Experimental results f_{cm}/MPa	Calculated results f_{cj}/MPa	Deviation of strength $\frac{f_{\text{cj}} - f_{\text{cm}}}{f_{\text{cm}}}$/%	Utilization coefficient of FRP strength k
RC50	60.3			
RC50C1	72.1	86.8	20.4	0.56
RC50C2	80.5	106.8	32.7	0.59
RC50B3	74.8	82.5	10.3	0.28

It can be seen from Tab. 2 that the calculated results are higher than the experimental results and the difference is from 10.3% to 32.7%. The reasons are described as follows:

1) During the deduction of calculation methods, three hypotheses were made. It might induce the difference.

2) During the experiment, there existed relative slippage between FRP skein and concrete cylinder because of the poor adhesive bond.

3) During the experiment, the testing data of compressive strength were discrete.

The utilization coefficients of FRP's compressive strength were from 0.28 to 0.29, which meant that the FRP's function was not fully utilized. Ref.[9] showed that when the concrete's stress reached the ultimate strength, the residue strength of FRP skeins would retard the total destruction of the concrete cylinder, thus the concrete's ductility was improved. Results also showed that CFRP could offer more lateral constraining force because of its high modulus and tensile strength. So the CFRP wrapping concrete had better tail load-bearing capacity than GFRP wrapping concrete.

4 Conclusion

When the concrete's compressive stress reached the ultimate strength, the virtual tensile stress of FRP was smaller than its ultimate tensile strength. So it was reasonable to introduce the utilization coefficients here. k value of CFRP was above 50% and that of GFRP was below 30%. The calculated results were higher than the experimental results. The difference was from 10.3% to 32.7%. This difference was mainly due to the poor interfacial bond of the FRP-concrete and discrete property of the testing data of compressive strength. If the adhesive property is better, reinforcement effect will be improved.

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FRP 约束高强混凝土轴心抗压强度的计算方法

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摘要: 建立了一个用于估算 FPR 加固混凝土轴心抗压强度的数学模型, 该模型引入了 FRP 强度发挥系数(套箍发挥系数). 实验结果表明, 混凝土达到极限强度时, FRP 并未达到极限强度, 其强度发挥系数在 0.28～0.59 之间, 与 FRP 的弹性模量有关. 该计算方法可用于估算 FRP 加固混凝土的轴心抗压强度, 其理论计算强度高于实测强度 10%～30%, 偏差主要来自 FRP 与混凝土的界面粘结状况不理想及混凝土抗压强度数据的离散性等.

关键词: 加固; 高强混凝土; FRP; 轴心抗压强度; 理论计算

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