Finite Element Analysis of Axial Compression Behavior of Damaged RC Columns Strengthened with GFRP Strips and Steel Fiber Mortar

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Abstract. Based on the experiment of damaged RC columns strengthened with GFRP strips and steel fiber mortar, this paper established a model using ABAQUS to perform the finite element simulation analysis and the extended analysis on the factors such as the spacing of GFRP strips, the number of layers and the strength of steel fiber mortar. The results indicate that: The smaller spacing of GFRP strips and the more layers bring the stronger constraint on the core part, the larger peak load on the composite structure and the better ductility; The larger strength of steel fiber mortar brings larger peak load but lower increased range; With the increased strength of steel fiber mortar, its ductility becomes worse, and the brittle failure becomes more obvious. Finally, according to the superposition method, the calculation equation of bearing capacity of damaged RC columns Strengthened with GFRP strip and steel fiber mortar was proposed. The calculated values basically agreed with the test values.

Keywords. GFRP, steel fiber mortar, damage, ABAQUS, calculation of bearing capacity

1. Introduction

With the acceleration of the urbanization process in China, the speed of building renewal is also gradually accelerating. Due to many adverse factors, numerous buildings often present structural damage, insufficient bearing capacity and other problems. How to take effective measures to delay damage has aroused more thinking. As the main stress component in concrete structure, column determines the safety of the whole structure, and its reinforcement seems more important.

As a kind of high-performance composite material, glass fiber composite material is widely used in projects because of its corrosion resistance, high strength and low price [1-3]. Steel fiber cement mortar has the characteristics of enhancement, crack resistance and good toughness, and its combination as a repair material can significantly improve
the mechanical properties such as the bearing capacity of components [4, 5]. Therefore, a new combination-GFRP strip and steel fiber mortar is proposed to reinforce the damaged RC column. At present, there are few studies on GFRP constraining the damaged concrete column. Most studies are about the mechanical properties of RC columns strengthened with GFRP and steel fiber mortar. The common damage repair process is also relatively simple. In order to better reinforce the components, the damaged RC column is repaired by steel fiber mortar first, and then the GFRP strip is added to restrain the column horizontally. This method can repair it and reinforce it with the strip hoop. This paper establishes the finite element model of damaged RC columns strengthened with GFRP strips and steel fiber mortar using ABAQUS finite element analysis software, verified the model accuracy, and analyzed the influence of many factors (spacing of GFRP strips, number of layers, strength of steel fiber mortar) on the bearing capacity. Finally, according to the superposition method, the calculation equation of bearing capacity of damaged RC columns strengthened with GFRP strip and steel fiber mortar was proposed. Comparing the calculated data and experimental data, it is found that the error is within 10%, which is in good agreement and can provide references for relevant studies.

2. Finite Element Model

The eccentric compression test of damaged RC columns strengthened with GFRP strip and steel fiber mortar has been completed before. The material properties and mechanical properties, specimen size, constraints, measurement point layout and loading system are shown in Literature [6]. Now, ABAQUS finite element software is used to establish the damage RC column model reinforced with GFRP strip and steel fiber mortar for simulation.

2.1. Material Constitutive

The parabolic plus straight-line constitutive model proposed by Lam and Teng in the later stage of Teng is selected as the concrete constitutive model [7, 8].

The compression and tension constitutive of steel fiber mortar are respectively from E. Hognesta constitutive of concrete and the calculation equation in Code for Design of Concrete Structures (GB50010-2010) [9].

GFRP is the orthogonal-specific material. When the limit strain of the fiber is reached, fracture damage occurs, with linear elastic mechanical properties. The constitutive expression is:

\[
\begin{align*}
\sigma_{\text{ef}} &= E_{\text{ef}} \varepsilon \quad \varepsilon \leq \varepsilon_{\text{ef}} \\
\sigma_{\text{ef}} &= 0 \quad \varepsilon > \varepsilon_{\text{ef}}
\end{align*}
\]

(1)

The steel constitutive model adopts the double broken line model.
2.2. Modeling

C3D8R solid unit is adopted for concrete, steel fiber mortar and upper and lower end plates, and T3D2 truss unit is adopted for reinforcement; S4R shell element is adopted for GFRP strip. The grid side length of RC column is divided by 0.025 m, with good convergence and high accuracy. The reinforcement framework is embedded in the concrete column (embedded region), and the upper and lower end slabs select control points and constrained areas for coupling constraints. The core concrete and steel fiber mortar adopt binding constraints (Tie) with the upper and lower end slabs respectively. The contact relationship between the core concrete and steel fiber mortar is binding constraints (Tie), and the contact surface between GFRP strip and steel fiber mortar is Tie contact.

2.3. Boundary Conditions and Loading Method

The bottom setting of the column is fully reinforced, i.e. U1=U2=U3=0 and UR1=UR2=UR3=0. The upper end restricts the displacement in X and Y directions, and applies the displacement load in Z direction, that is, U1=U2=0. The loading process is divided into two processes. The first process is the axial pressure predamage of RC column, and the second process is the overall axial pressure failure of the reinforcement column.

3. Verification of Finite Element Model

It can be seen from Figure 1, the simulation of damaged column reinforced with GFRP strip and steel fiber mortar is basically consistent with the test load-displacement curve. It increases linearly in the elastic stage, the slope begins to decrease in the plastic stage, the difference between peak load and peak displacement is controlled within 10%, and the change trend in the descending section is basically the same. It shows that the simulation is consistent with the test results. By simulating the typical specimen GSSFRC-2 and comparing the test with the simulated deformation diagram in Figure 2, it is found that the deformation diagram of the simulated specimen is consistent with the failure phenomenon in the test process, which is mainly based on the expansion tensile failure of the middle GFRP strips or the crushing failure of the middle concrete. The model is more accurate.

4. Finite Element Parameter Extension Analysis

The finite element model of damaged RC columns strengthened with GFRP strips and steel fiber mortar is established on the test basis. The model correctness is verified through comparing load-displacement curve and deformation pattern. In order to better study the axial compression behavior of the composite reinforced column, and better guide the design of the composite reinforced column, an extended analysis is performed on other parameters to study its mechanical property.
Figure 1. Comparison between computational load-displacement curve and test curve of columns reinforced with GFRP strips and steel fiber mortar.

(a) Initial diagram  (b) Deformation diagram  (c) Test specimen

Figure 2. Comparison of the typical specimen deformation diagram.

4.1. Relationship between Bearing Capacity and GFRP Strip Layers

Taking GSSFRC-2 specimen as an example, the layer design is used to change the number of winding layers and observe the damage phenomenon. In case of less layers, the strips are broken first, and then the steel fiber mortar between the strips is crushed; in case of more layers, the reinforcement layer of steel fiber mortar is crushed, and then the strip is broken.

The load-displacement curve in Figure 3 shows that: the curves basically coincide in the elastic phase. At this time, GFRP strip has not played a role. With the increase of the number of layers, the greater the slope means the higher the peak load. The growth trend is fast before the four layers and slows down after four years. Analyze the reasons: The increase in the number of strip layers can effectively increase the constraint to some
extent. However, when the thickness gradually increases, the bearing capacity provided by lateral constraints is also limited; As the number of layers increases, the constraint gradually increases, the descending segment slope decreases, and the ductility increases.

Figure 3. Effect of winding layers of GFRP strip on load-displacement curve of specimen.

4.2. Relationship between Bearing Capacity and GFRP Strip Spacing

Figure 4 shows different strip widths. According to the load-displacement curve of different strip spacing shown in Figure 5, the influence of different strip spacing on the limit bearing capacity is analyzed: with the same constraint amount and different distribution, the curve shape basically coincides, and the difference of load peak value is very small. The constraint is slightly better when the strip is wide but less influential. It shows that changing the spacing of single-layer with the same constraint will not affect its bearing capacity.

Figure 4. Schematic diagram of the strips at different segments.

Figure 5. Effect of different segments on the specimen load-displacement curve.
4.3. Relationship between Bearing Capacity and Axial Compressive Strength of Steel Fiber Mortar

As shown in Figure 6a, GSSFRC-2 specimen is taken as the example to analyze the influence of steel fiber mortar strength on the bearing capacity of damaged column reinforced with GFRP strips and steel fiber mortar. The bearing capacity of the specimen increases with the strength of steel fiber mortar, but the increase amplitude decreases with the strength. The greater strength means the worse ductility, and the more obvious brittle destruction characteristics. Analyze the reasons: GFRP strip constraint is weak. Steel fiber mortar plays a main role in the reinforcement constraint behavior. The lateral constraint is poor, and brittle failure is easy to occur in the later stage. As shown in Figures 6b and 6c, with the increase of the damage degree, the increasing strength of steel fiber mortar will have an obvious reinforcement effect. But with the greater slope of the descending curve segment, it will bring the worse ductility and the increasing possibility of brittle failure.

![Figure 6. Effect of steel fiber mortar strength on GSSFRC specimen load-displacement curve.](image)

5. Calculation Equation of Bearing Capacity

Based on the superposition principle, GFRP strip constrains the concrete column. The axial pressure strength is mainly determined by the concrete restraint stress of the strip and the concrete strength. The equation of axial pressure bearing capacity is:
wherein: \(k_1\) stands for the lateral restraint coefficient; \(f_i\) stands for the lateral restraint stress. \(\Psi\) stands for the damage coefficient; \(\alpha\) stands for the strength utilization coefficient (0.8); \(f_{c1}\) stands for the axial compressive strength of concrete; \(f_{c2}\) stands for the axial compressive strength of steel fiber mortar; \(A_{c}\) stands for the cross-sectional area of concrete column; \(A_{s}\) stands for the cross-sectional area of reinforcement part of steel fiber mortar. Select according to the test data fitting equation in Reference:

\[
\psi = -2.625 \beta^2 + 3.575 \beta - 0.35
\]

wherein: \(\beta\) means the damage degree in a range of 0.1-1 (0.6 for level 1 damage; 0.8 for level 2 damage; 1.0 for level 3 damage). Zhou [10] established a simplified calculation model of GFRP strip constraining the concrete column strength, and proposed the interval constraint coefficient \(K_g\):

\[
k_g = \left(1 - \frac{\delta}{2d}\right)^2
\]

Since the constraint provided by the longitudinal reinforcement has little influence, in order to simplify the calculation, the simplified equation of Zhou Changdong can be adopted, which is put into equation (2):

\[
N_0 = \psi f_{c1} A_{c1} + \alpha f_{c2} A_{c2} + k_1 k_g f_i + f_s A_s
\]

\[
k_i = \frac{N_0 - \psi f_{c1} A_{c1} - \alpha f_{c2} A_{c2} - f_s A_s}{f_i k_g}
\]

The meaning of each parameter is the same as described above.

Using the fitting equation \(\gamma = \alpha e^b\) and considering GFRP strip spacing, layers, RC column damage degree and influence of steel fiber mortar strength on bearing capacity, the data are included for the regression fitting:

\[
k_i = 10.2 \frac{f_i}{f_{co}}^{(-0.92)}
\]

Equation (7) is put into equation (5) to obtain the calculation equation of bearing capacity:
The parameters are put into equation (8), the calculated value $N_u$ of each specimen are obtained and compare it with the test value $N_{u0}$. It is found that the average error is about 0.25%, and the standard deviation of the ratio between the simulation value and the test value is 0.02. The analysis of the calculated value and the test value is as shown in Figure 7. It can be seen intuitively that the results are consistent within the range of 10%.

\[
N_u = (-2.625\beta^2 + 3.575\beta - 0.35) f_{c3}^r A_{s3} + 0.8 f_{c3}^r A_{s3} + 10.2 \left( \frac{f_{s1}}{f_{c3}} \right)^{0.5} - \frac{f_{s1} f_{c3}}{2d} \left( 1 - \frac{s}{2d} \right)^2
\]  

(8)

6. Conclusion

(1) The influence of GFRP strip spacing on axial compression behavior is analyzed. With the same constraint amount and different distribution, the difference of load peak value is very small; With the same distribution form and different restraint quantities, the more constraint means the larger peak load and the better constraint effect, and the bearing capacity is increased by about 4.76%. The stronger constraint effect means the smaller slope in the descending segment and the better ductility.

(2) The influence of GFRP strip layer on axial compression behavior is analyzed. As the number of layers increases, the constraint gradually increases, the descending segment slope gradually decreases, and the ductility increases. Peak load increases with the number of layers. However, it grows rapidly in the early stage, and the growth trend slows down after four layers.

(3) By analyzing the influence of different parameters on the limit bearing capacity of the specimen, the limit bearing capacity equation of damaged RC column reinforced with GFRP strips and steel fiber mortar is established. The calculated value agrees well with the test value to meet the engineering requirements.
References


