The experimental study on damaged square columns strengthened by reinforcement mesh steel fiber

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Abstract. Eight common reinforced concrete columns were damaged by different sizes loads. The damaged reinforced concrete columns were strengthened by reinforcement mesh steel fiber. Three identical test pieces were made to explore the dispersion of the reinforcement method. The axial compression experiment was researched by factor of mortar types, damage degree, the lateral and longitudinal spacing. The formula of the axial bearing capacity of damaged square columns were strengthened by reinforcement mesh steel fiber was proposed. The calculated values agreed well with the experimental results. The test results showed that the damaged square columns were strengthened by reinforcement mesh steel fiber was an effective reinforcement method. This method was less discrete and can not only improve the ultimate bearing capacity, cracking load ductility and anti-cracking ability, but also the mechanical properties and failure mode can be effectively improved.

1. Introduction
The reinforcement method of reinforcement mesh steel fiber is a new reinforcement technology. The principle of this method is to form a reinforcement thin layer through the combination reinforcement mesh and steel fiber, and form a whole with the original component concrete to make it bear the force together. Research at home and abroad shows that the use of reinforcement mesh steel fiber reinforcement method can significantly improve the strength, toughness, crack resistance and ductility of the strengthened structure. The research on the reinforcement of concrete columns by this reinforcement method mainly focuses on the reinforcement of undamaged columns, while most of the damaged columns need to be strengthened in practical projects. Therefore, in this paper, the percentage of peak load of preloaded reinforced concrete columns is taken as the damage index of columns: 60% of the load limit load is first-class damage, 80% is second-class damage, and the destruction is third-class damage. A total of 8 damaged columns were fabricated. Taking the mortar type, damage degree, transverse and longitudinal spacing of reinforcement mesh as the influencing factors, the axial compression test of damaged columns strengthened with reinforcement mesh steel fiber is carried out, and the discreteness of reinforcement method is explored.
2. Test of ordinary reinforced concrete columns

2.1. Test purpose
The raw materials and mechanical indexes of damaged steel reinforced concrete columns strengthened with reinforcement mesh steel fiber are obtained as the basis for the comparison of axial compressive properties of reinforced concrete columns before and after reinforcement.

2.2. Component design and production
In this test, 8 ordinary concrete columns with column length of 1000mm are pre damaged. The design parameters are shown in table 1, and the design details of concrete columns are shown in figure 1.

![Figure 1. Detail drawing of Concrete columns design](image)

| Component number | Damage degree | Applied load                  |
|------------------|---------------|-------------------------------|
| RC-1             | Tertiary damage | Crush                        |
| RC-2             | Tertiary damage | Crush                        |
| RC-3             | Secondary damage | Ultimate bearing capacity 80% |
| RC-4             | Secondary damage | Ultimate bearing capacity 80% |
| RC-5             | Secondary damage | Ultimate bearing capacity 80% |
| RC-6             | Secondary damage | Ultimate bearing capacity 80% |
| RC-7             | Secondary damage | Ultimate bearing capacity 80% |
| RC-8             | Primary damage | Ultimate bearing capacity 60% |

2.3. Material Properties
42.5 ordinary silicate cement for pouring, the mix proportion: m(cement):m(water):m(sand):m(stone) =500:205:593:1152. Conduct material property test on the manufacturing materials, the data obtained are as follows:

1. C40 concrete, measured cube compressive strength $f_{cub}=45.2\text{N/mm}^2$;
2. Longitudinal reinforcement HRB400, measured strength $f_y=369.5\text{N/mm}^2$;
3. Stirrup HPB300, measured strength $f_y=234.9\text{N/mm}^2$. 

![Table 1. The design parameter of specimen](table)
2.4. Loading device and system
The test was carried out in the hall of Structural Laboratory of Xi'an University of technology, loading 5000KN long column pressure test machine using a microcomputer control electro-hydraulic servo. The specific test device is shown in figure 2, the loading method of load displacement joint control is adopted in this test, Loaded method is graded, the loading load shall be applied by \(1/15\) of the ultimate load, the load holding time is 10min. After the load reaches 0.8\(N_u\), change to displacement control, the load rate is 1mm/min. Until the load of the test piece drops to 75% of the peak load to stop loading. The axial pressure and vertical displacement are automatically acquired by the electro-hydraulic servo microcomputer system.

![Figure 2. The diagram of test loading device](image)

2.5. Test results
The test results were as follows:

| Component number | Crack load (kN) | Failure load (kN) |
|------------------|----------------|------------------|
| RC-1             | 544            | 1142             |
| RC-2             | 816            | 1370             |
| RC-3             | 544            | 1096             |
| RC-4             | 816            | 1096             |
| RC-5             | 856            | 1096             |
| RC-6             | 856            | 1096             |
| RC-7             | 816            | 1096             |
| RC-8             | 749            | 822              |

3. Experimental survey of reinforcing damaged reinforced concrete columns with reinforcement mesh steel fiber

3.1. Test purpose
1) Explore the influence of various influencing factors on the axial compression performance of reinforced columns.
2) The axial compression performance of reinforced concrete square columns before and after reinforcement is compared and analyzed.
3.2. Component design and fabrication

Strengthening 8 damaged ordinary reinforced concrete columns obtained in Section 1, reinforcement method operation process is: Damage column chisel ⇒ Making steel network ⇒ Damaged column add reinforcement cage ⇒ Formwork pouring ⇒ Curing. The details of reinforced column are shown in figure 3, design parameters are shown in table 3, among them, SW is a column of reinforcing steel mesh ordinary mortar. SSW1~SSW5 are columns strengthened with reinforcement mesh steel fiber mortar. The parameters of SSW2 (1) ~ SSW2 (3) are identical.

![Figure 3. Detail drawing of reinforcement columns design](image)

### Table 3. The design parameter of specimen

| Original column number | Damage degree of primary column | Reinforced rear column | Reinforcement spacing (longitudinal × Horizontal) | Whether to add steel fiber |
|------------------------|--------------------------------|------------------------|---------------------------------------------------|--------------------------|
| RC-1                   | Tertiary damage                | SW                     | 50 × 50                                            | Not added                |
| RC-2                   | Tertiary damage                | SSW3                   | 50 × 50                                            | Added                    |
| RC-3                   | Secondary damage               | SSW2 (1)               | 50 × 50                                            | Added                    |
| RC-4                   | Secondary damage               | SSW2 (2)               | 50 × 50                                            | Added                    |
| RC-5                   | Secondary damage               | SSW2 (3)               | 50 × 50                                            | Added                    |
| RC-6                   | Secondary damage               | SSW4                   | 50 × 100                                           | Added                    |
| RC-7                   | Secondary damage               | SSW5                   | 100 × 50                                           | Added                    |
| RC-8                   | Primary damage                 | SSW1                   | 50 × 50                                            | Added                    |

3.3. Material performance

42.5 ordinary silicate cement for pouring, steel fiber parameters are 1% of cement mortar volumetric parameters, the mix proportion is m(cement):m(water):m(sand):m(steel fiber)=1134: 597: 269: 39. Material performance test for materials is obtained as follows:

1. Reinforcement mesh is bound with Φ6 steel bars, measured yield strength $f_{y3}=234.9$ N/mm²;
(2) The strength of the mortar is M50, measured cube compressive strength $f_{mc}=53.4\text{N/mm}^2$;
(3) The loading system and measurement contents of this batch of specimens are the same as those in Section 1.3.

3.4. Test process and form
The failure process of each specimen of reinforced column was similar.

At the beginning of loading, there is no obvious phenomenon in each column, in the elastic phase, and the mechanical performance is relatively close. As the load increased, when the load reached 40% of the limit load, the upper portion of the test column began to appear vertical cracks, and the test piece entered the elastoplastic stage. With the increase of load, the fine cracks gradually increased, the crack width increased, and the cracks began to extend to the middle of the column. When the load reached 70% ~ 80% of the ultimate load, the concrete column began to expand slightly laterally. When the load approached the peak value, the vertical crack increased obviously. After the peak load, the test piece did not show a large brittleness like reinforced concrete axial pressure short column, and the reinforcing column bearing capacity decreased.

The cracks were observed for SSW3 tests that had fallen, and it was found that the steel fiber pulled the damaged concrete to prevent it from falling off.

Stripping the test column mortar layer, found that the mortar and the steel network and the built-in concrete column are very good, no peeling and slippage. Some column destruction diagrams are shown in figure 4.

![Image of reinforced RC-2 column](image1)
(a) No reinforced RC-2 column

![Image of SSW3 column after reinforcement](image2)
(b) SSW3 column after reinforcement

![Diagram of cracking when SSW3 is damaged](image3)
(c) Schematic diagram of cracking when SSW3 is damaged

**Figure 4.** The failure diagram of reinforcement columns
3.5. Test results and analysis

This paper describes the experimental results of damaged reinforced concrete columns strengthened with reinforcement mesh steel fiber mortar under axial compression according to different groups of influencing factors.

(1) Effect of steel fiber mortar on axial compressive properties.

The load-displacement curves of SW and SSW3 are shown in Figure 5.

The SW of load-displacement curve is basically the same as SSW3, indicating that steel fiber does not participate in the work before large area cracking. The cracking load of SW is 33.3% smaller than that of SSW3, indicating that the incorporation of steel fiber into mortar layer can inhibit the generation of cracks.

The ultimate load SW is 2.78% larger than that of SSW3, indicating that whether the use of steel fiber mortar has little effect on the bearing capacity. From the curve descending section, the displacement of the descending section of SSW3 is 127.02% larger than that of SW, so the steel fiber mortar can improve the ductility of the reinforced column (in this paper, the ductility is defined as the displacement of the descending section, the larger the displacement of the descending section, the better, the ductility).

(2) Discreteness of reinforcement method with reinforcement mesh steel fiber mortar and effect of reinforcement mesh spacing on axial compression performance.

The load-displacement curves of SSW2, SSW4 and SSW5 are shown in Figure 6.

SSW2(1), SSW2(2) and SSW2(3) are columns with the same structure. There is little difference in the cracking load, ultimate load and load-displacement curve, indicating that the reinforcement method is less discrete.

The ultimate load of SSW2(2) is 5.23% higher than that of SSW4 and 8.19% higher than that of SSW5. The ultimate displacement of SSW2(2) is 134.4% higher than that of SSW4 and 160% higher than that of SSW5, indicating that the spacing between transverse reinforcement and longitudinal reinforcement of reinforcement mesh affects the bearing capacity and ductility of reinforced columns. When the spacing between reinforcement meshes is closer, the bearing capacity is greater, and the ductility is better. The ultimate load of SSW4 is 2.8% higher than that of SSW5, indicating that the effect of longitudinal reinforcement on the improvement of bearing capacity is better than that of transverse reinforcement. The displacement of the descending section of SSW5 is 31.6% larger than that of SSW4, indicating that the transverse reinforcement of the reinforcement mesh is better than the longitudinal reinforcement of the steel mesh.

(3) Influence of damage degree of built-in concrete column on axial compression performance.

The load-displacement curves of SSW1, SSW2(2) and SSW3 are shown in Figure 7.

The cracking load of SSW3 and SSW2(2) is 8.14% larger than that of SSW1. The reason is that the damage of the built-in concrete columns of SSW3 and SSW2(2) is the most serious when pre-damaged, so there are more loose concrete hiselled off, so there are also more steel fiber mortar used in reinforcement. The large amount of steel fiber leads to the late development of cracks in SSW3 and SSW2. The bearing capacity of SSW3 is 24.8% smaller than that of SSW2(2) and 10.7% smaller than that of SSW1. This is because the built-in concrete column of SSW3 is crushed and its bearing capacity decreases most. The bearing capacity of SSW1 is 15.79% lower than that of SSW2(2). This is because the bearing capacity of built-in columns with primary damage and secondary damage does not decrease much, so the bonding force between new and old concrete has become the primary factor affecting the bearing capacity. A certain degree of built-in concrete damage can improve the bonding force between the old and new concrete, so as to improve the ultimate load. Therefore, SSW1 has bond slip failure between the old and new concrete, while SSW2 does not, so the bearing capacity of
SSW2 is higher. The descending displacement of SSW3 is much larger than that of SSW1 and SSW2(2), indicating that the more steel fiber mortar used in reinforcement, the better ductility.

3.6. Comparative analysis of axial compression performance of reinforced concrete square columns before and after reinforcement

The load displacement curve of RC-2, SSW1, SSW2, SSW3 is shown in Figure 8. Bearing capacity: the ultimate bearing capacity of SSW1 was increased by 79.4%, the ultimate bearing capacity of SSW2 increased by 113.1%, and the ultimate bearing capacity of SSW3 increased by 60.1%. The displacement of the descending segment: the displacement of the descending segment of SSW1 increased by 65.2%, the displacement of the descending segment of SSW2 increased by 142.3%, and the displacement of the descending segment of SSW3 increased by 627.9%, indicating that the reinforcement of concrete with obvious cracks using reinforcement mesh steel fiber mortar can greatly improve its bearing capacity, and the reinforcement of completely damaged concrete columns can greatly improve its ductility.

![Fig.5 SW、SSW3 load-displacement curve](image1)
![Fig.6 The load-displacement curve of SSW2、SSW4、SSW5](image2)
![Fig.7 SSW1, SSW2, SSW3 load-displacement curve](image3)
![Fig.8 RC-2,SSW1, SSW2(2), SSW3 load-displacement curve](image4)
4. A formula for axial compression of damaged concrete columns strengthened with reinforcement mesh steel fiber

References [9]~[10] put forward the formula of Undamaged Concrete Column Strengthened with reinforcement mesh cement composite mortar: 

\[ N = 0.9(N_1 + N_2 + N_3) \]

In the formula: \( N \) is the axial pressure of the strengthened member; \( N_1 \) is the axial pressure borne by the original column when it is not restrained; \( N_2 \) is the axial pressure borne by the reinforcement layer; \( N_3 \) is the increased value of the axial pressure borne by the original column concrete due to the restraint of the reinforcement layer [10].

The theoretical derivation of formulas in the above literature is based on the reinforcement of non-destructive columns, and the reinforcement of damaged columns has different stress conditions. The test showed that the damage degree of built-in concrete column was a key factor which affecting the ultimate bearing capacity of reinforced column, and the damage of built-in concrete column is mainly concentrated in concrete damage. Therefore, the \( N_1 \) formula is introduced into the damage coefficient \( \varphi \) and modified as 

\[ N_1 = \varphi f_c A_c + f_c' A_s' \]

\( \varphi = -3.33 \omega + 3.557 \)

In the formula, \( \omega \): 0.8 for secondary damage and 1.0 for tertiary damage; \( f_c \) is axial compressive strength of concrete; \( A_c \) is the area of built-in reinforced concrete column; \( f_c' \) is the axial compressive strength of built-in concrete longitudinal reinforcement; \( A_s' \) is the total area of built-in concrete longitudinal reinforcement.

Because the damaged built-in reinforced concrete column is loose, it is chiseled out and replaced by steel fiber mortar, and the previous test shows that the effect of reinforcement mesh steel fiber reinforcement method is more obvious for the damaged reinforced concrete column. Therefore, it is necessary to introduce the enhancement factor \( \alpha \) into the \( N_2 \) term (the bearing capacity of the strengthened layer) to improve, that is 

\[ N_2 = \alpha \{ f_c' A_{s'} + f_{mc} [2 t_m (b + h) - A_s'] \} \]

In this paper, \( \alpha \) is taken as 3.1; where \( f_c' \) is the design value of axial compressive strength of longitudinal reinforcement of reinforcement mesh; \( A_{s'} \) is the total area of longitudinal reinforcement of reinforcement mesh; \( f_{mc} \) is the design value of axial compressive strength of steel fiber mortar; \( t_m \) is the thickness of reinforcement layer; \( b \) is the width of specimen; \( h \) is the length of the specimen. The calculation method of \( N_3 \) is shown in reference [10]. The comparison between specific calculation data and test data is shown in Table 8. The average ratio of the theoretical calculated value to the actual test value is 0.968, and the standard deviation is 0.025. The calculated value is in good agreement with the test value, and has a certain safety reserve.

| Specimen number | Calculated value (kN) | Test value (kN) | Calculated value/Test value |
|-----------------|-----------------------|----------------|---------------------------|
| SSW2(2)         | 2722.711              | 2919           | 0.93                      |
| SSW3            | 2204.829              | 2194           | 1                         |
| SSW4            | 2691.211              | 2774           | 0.97                      |
| SSW5            | 2614.521              | 2698           | 0.97                      |

Note: due to the bond slip failure of old and new concrete of SSW1 test column in this test, and the material performance is not fully brought into play, the data of SSW1 test column is not listed in the table.

5. Conclusion

(1) Because the steel fiber can hold the damaged concrete and prevent it from falling off, therefore, in reinforcement mesh steel fiber reinforced mortar reinforcement method, steel fiber mortar has better ductility than ordinary mortar.

(2) Because the reinforcement mesh steel fiber mortar has a good wrapping effect on the damaged column, the reinforcement mesh steel fiber reinforcement method has less discreteness and the
reinforcement state is relatively stable. The transverse reinforcement mainly plays the role of wrapping, while the longitudinal reinforcement participates in the stress. Therefore, the longitudinal reinforcement of densified reinforcement mesh can greatly improve the bearing capacity, and the transverse reinforcement of densified reinforcement mesh can greatly improve the ductility.

(3) Because the damaged loose built-in concrete will be chiseled out in the process of column reinforcement and steel fiber mortar is added, the built-in concrete will be damaged and the ductility of the reinforced column will be improved most. There are obvious cracks in the built-in column, and the bearing capacity of the reinforced column is increased the most.

(4) The above derived calculation formula is in good agreement with the test results, but due to the limited influencing factors considered in this test, other influencing factors of reinforcement mesh steel fiber mortar reinforced pre-damaged concrete columns need to be studied to improve the calculation formula.

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