Finite Element Analysis of the Mechanical Performance of Reinforced Concrete Beams with different Steel Plate Strengthening Rates

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Abstract. In order to study the effect of different ratios of steel plate strengthening the bottom of reinforced concrete beams on the mechanical properties of the beam, based on the area of the bottom of the beam, various steel plate reinforcement schemes of 25%, 50%, 75% and 100% were designed. ABAQUS is used for static load calculation and comparative analysis with unreinforced reinforced concrete. The results show that: (1) Different ratios of steel plate strengthening the bottom of reinforced concrete beam can improve the bearing capacity of the beam, but the growth of the bearing capacity slows down after the steel plate ratio reaches 75% of the area of the beam bottom; (2) Reinforcing steel plates with different ratios at the bottom of the beam can improve the flexural performance of the beam. It is suggested that the steel plate reinforcement ratio should be selected reasonably in engineering practice.

1. Introduction
At present, reinforced concrete structures are widely used in industrial and civil buildings. The structure has rich design experience, mature construction technology and good market potential. At the same time, it is inevitable that structural components including beams, slabs, and columns are damaged due to some design defects, different construction levels, improper use in the later period, and natural disasters such as earthquakes, resulting in insufficient structural bearing capacity. It appears that a large number of concrete structures need to be reinforced [1-3]. As the main load-bearing component of reinforced concrete beam, there are many researches on its reinforcement. For example, Peng J X (2015) [4] conducted a pre-compression test on 12 reinforced concrete beams with a corrosion rate of 10% after reinforcement with steel plate anchors, and showed that the reinforcement with steel plate anchors can significantly improve normal service performance. Liu B (2015) [5] used horizontal low-cycle repeated load tests to demonstrate the seismic performance of carbon fiber reinforced concrete beams with different reinforcement ratios and steel plate reinforced concrete beams. Cai Z W (2017) [6] used steel plates to reinforce the side of concrete beams, and conducted mechanical tests after the beams were damaged by high-temperature tests, which proved that reinforcing steel plates can significantly increase the ultimate load. Liu T B (2017) [7] used a nonlinear analysis method to analyze reinforced concrete beams strengthened with steel plates, and deduced the nonlinear differential equations of reinforced concrete beams strengthened with steel plates in terms of steel plate tension. Zhou C L (2019) [8] studied the seismic performance of concrete frame joints strengthened by outer steel plate, which showed that the outer steel plate has a good reinforcement effect. Zhang Y Q (2019) [9] conducted mechanical tests
on precast concrete double T slabs reinforced with steel plates, and the results showed that the peak load-bearing capacity of the specimens reinforced with steel plates was increased by about 2.17 times. Wang Q (2019) [10] conducted flexural tests on reinforced concrete beams reinforced with steel plate and natural basalt fiber reinforced composite materials, and showed that the reinforcement method can effectively improve the bearing capacity and stiffness of the beam. Gao S (2019) [11] obtained the ultimate bearing capacity and shear failure mode of four pieces of damaged reinforced concrete simply supported T-beams by steel-concrete combination reinforcement and shear bearing capacity test.

This research takes the reinforced concrete beams strengthened with different steel plate ratios at the bottom of the beam as the research object, and uses the ABAQUS finite element analysis software to build models and analyze the bearing capacity and flexural performance of the reinforced concrete beam before and after the steel plate is strengthened at the bottom of the beam.

2. Research model design

2.1. Model design

For comparative analysis, two groups of beams were designed, the one was ordinary reinforced concrete beams (RCB), and the other was beams reinforced by steel plates with different proportions at the bottom of ordinary reinforced concrete beams. According to the area of the bottom of the beam, four ratios of 25%, 50%, 75% and 100% were designed. Steel plates with a reinforcement ratio of 50% and 75% can be divided into two methods: one steel plate in the middle and two steel plates at both ends. The schematic diagram of the steel plate reinforcement rate at the bottom of the beam is shown in Figure 1 (a). The shaded area in the figure represents the percentage of the steel plate to the bottom area of the beam. The beam has a span of 6 m and a cross-sectional dimension of 200 mm × 500 mm. The beam cross-section reinforcement diagram and the cross-sectional cross-sectional diagrams are shown in Figure 1 (b) and (c).

Figure 1. Schematic diagram of the model: (a) Schematic diagram of steel plate reinforcement rate at the bottom of beam (b) Reinforcement diagram of beam section (c) Section 1-1, 2-2, 3-3.
2.2. Material parameters\textsuperscript{[12]}

The strength grade of concrete is C20, and the elastic model is 25,500 MPa, and the Poisson's ratio is 0.2. The steel bars are shown in Figure 1 (c), ① means the stirrup, the strength grade is HRB300 steel bar, and the diameter is 8mm, and the stirrup spacing is 200 mm; ② represents the reinforcement in the compression zone, with a strength grade of HRB400, with a diameter of 12 mm; ③ represents the reinforcement in the tension zone, and the tension zone is designed to be 3 steel bars with a strength grade of HRB400, with a diameter of 18mm. The steel plate strength grade is Q235, and the thickness of the steel plate is 2 mm. The modulus of elasticity of all steels is 210,000 MPa, and the Poisson's ratio is 0.3.

2.3. Finite element model establishment

The ABAQUS finite element software were used for modeling and analysis, solid elements were used for concrete, and the truss elements were used for reinforcement. The overall modeling method was adopted, and the bond-slip performance between steel bars, steel plates and concrete was not considered. Loading was carried out in the middle of the beam, and the method of loading was displacement loading, and the size is 60 mm. The schematic diagram after establishing the model and dividing the mesh is shown in Figure 2.

3. Results and discussion

3.1. Analysis of the relationship between force and displacement

After ABAQUS calculation, the relationship between the bearing reaction force and displacement of the two groups of beams under displacement load is shown in Figure 3. (0%, 25%, 50%, 75% and 100% respectively indicate the proportion of the steel plate attached to the bottom of the beam, 50%-Side and 75%-Side respectively indicate the steel plate attached to the bottom section of the beam along the longitudinal sides).
It can be seen from Figure 3(a) that under displacement load, the bearing capacity of ordinary reinforced concrete beams is generally much smaller than that of beams reinforced by steel plates with a ratio of 25% pasted to the bottom of the beams. The bearing capacity of those with 25% and 50% steel plate-reinforced beams are successively less than the bearing capacity of beams reinforced with 50% and 75% steel plates. The bearing capacity of beams with 75% steel plates gradually approaches that of beams with 100% steel plates. It can be seen from Figure 3 (b) that for the beams reinforced with 50% and 75% steel plates pasted at the bottom of the beam, the bearing capacity of the steel plate pasted at the middle of the bottom of the beam is basically the same as that at the two sides of the bottom of the beam (50%-Side and 75%-Side).

Table 1. Maximum bearing capacity of two groups of beams.

| Model          | Bearing capacity/kN | Increase value |
|----------------|----------------------|----------------|
| 0%             | 97.25                |                |
| 25%            | 112.92               | 16.11%         |
| 50%            | 120.60               | 24.01%         |
| 50%-Side       | 119.38               | 22.76%         |
| 75%            | 128.13               | 31.75%         |
| 75%-Side       | 125.41               | 28.96%         |
| 100%           | 132.07               | 35.80%         |

The maximum bearing capacity of the two groups of beams is shown in Table 1. It can be seen that the maximum bearing capacity of reinforced concrete beams reinforced with 25%, 50%, 75%, and 100% steel plates at the bottom of the beam is 16.11%, 24.01%, 31.75% and 35.80% higher than those of beams without steel reinforcement. For those beams reinforced with 50% and 75% steel plates, the bearing capacity obtained by using one steel plate to strengthen in the middle is slightly larger than the bearing capacity obtained by strengthening two steel plates on both sides. In addition, in terms of initial stiffness, the initial stiffness of beams reinforced with 25% steel plate is similar to that of ordinary reinforced concrete beams. The initial stiffness of beams reinforced with 50%, 75%, and 100% steel plates is greater than that of beams not reinforced with steel plates. For those beams reinforced with 50% and 75% steel plates, the initial stiffnesses obtained by the middle reinforcement and the two sides reinforcement are similar. The results show that: under the same load, without considering the bond slip between the steel plate and concrete, the method of strengthening the beam with steel plate can significantly increase the bearing capacity of the beam, and the bearing capacity increases with the increase of the steel plate ratio. However, when the ratio reaches 75%, the carrying capacity increases slowly relative to the previous ratio and gradually tends to the 100% ratio; At the same time, the method of strengthening the beam with steel plate can improve the initial stiffness of the beam.

3.2. Analysis of flexural performance
The ABAQUS software is used for data collection to obtain the bending moment values at the end and the middle of the beam. The bending moment diagrams of the two groups of beams under the load are drawn along the span direction as shown in Figure 4.
It can be seen from Figure 4 that the mid-span bending moment of the designed ordinary reinforced concrete beam is 32.52 kN·m, and the mid-span bending moment of the beam reinforced with 25% steel plate is 52.53 kN·m, which is an increase of 61.5% compared with the former; On this basis, after doubling the area of the reinforced steel plate (50%), the mid-span bending moment of the beam is 57.08 kN·m, and the bending moment of the reinforced concrete beam is increased by 75.5%. After the steel plate reinforcement area reaches 75% of the bottom area of the beam, the mid-span bending moment of the beam increases sharply by 107.1%, which doubles as much; The bending moment after the full-scale reinforcement of the steel plate at the bottom of the beam is 77.48 kN·m, which is a significant increase in the bending moment compared with ordinary reinforced concrete beams, reaching 138.3%. The results show that: without considering the bond slip between steel plate and concrete, the method of reinforcing steel plate at the bottom of reinforced concrete beam can improve the flexural performance of the beam, and as the proportion of reinforced steel plate increases, the flexural performance of the beam is increased significantly.

4. Conclusion
Taking the area of the bottom of the ordinary reinforced concrete beam as the benchmark, taking 25%, 50%, 75% and 100% of the area as the design steel plate size, and strengthening the bottom of the beam, using ABAQUS software for finite element analysis, and the results are as follows:

(1) Under the same displacement load, using different ratios of steel plate reinforcement at the bottom of the beam can improve the load-bearing capacity of the beam, and the load-bearing capacity increases with the increase of the steel plate ratio. When the ratio reaches 75%, the load-bearing capacity grows slowly. It is recommended to choose a reasonable ratio of steel plate reinforcement.

(2) Reinforcing steel plates with different ratios at the bottom of the beam can improve the bending resistance of the beam. The greater the increase ratio, the stronger the bending resistance of the beam.

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