

## Research Article

# Model Construction and Simulation Study on Bending Performance of Strengthened RC Beam in Externally Prestressing Industrial Reclaimed Steel Wire

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Strengthening with external prestressing is a kind of reinforcement method which imposes prestress on concrete by setting prestressed steel bar outside concrete, a new strengthening with external prestressing technology can be put forward by using industrial reclaimed steel wire instead of prestressing steel bar. High-quality steel wire is extracted from waste tire after stripping and derusting, and this kind of industrial reclaimed steel wire with high tensile strength and good toughness is applied to building reinforcement by externally prestressing method; it can provide a new research direction for the country's green, low-carbon, and high-quality development. In this paper, the new strengthening with external prestressing technology is used to study the bending static load test of test beams under different working conditions. The influence of reinforcement material and rotational degree on the bending performance of RC beam is discussed. The results show that the ultimate bearing capacity of the flexural members with industrial recycled steel wire is more effective under the new external prestressed reinforcement method. Under the same reinforcement method, when the reinforcement materials are the same, the increase of prestress can effectively improve the bearing capacity of flexural members in the reinforced beams with prestress of 30%, 40%, and 50%, respectively. In order to verify the reinforcement effect of industrial recycled steel wire on the bending performance of RC beam from multiple perspectives, the numerical simulation was carried out on the concrete specimens reinforced with different degrees of woven reinforced wire, and the simulation results were in good agreement with the experimental results. This study provides a new research direction for the recycling of industrial reclaimed steel wire and the reinforcement of concrete components and has a good promotion, role, and theoretical support for subsequent research.

## 1. Introduction

In 2020, China put forward the strategic goal of carbon peak and carbon neutrality, striving to reach the peak by 2030 and striving to achieve carbon neutrality by 2060. In 2020, Chinese steel industry carbon emissions accounted for 15% of the total national carbon emissions; reducing carbon emissions by recycling steel is one of the most effective ways [1].

According to the statistical analysis of effective data, Chinese tire production has been at the forefront of the world. In December 2021, Chinese rubber tire output was 82.435 million, an increase of 0.6 percent year on year; in 2021, Chinese rubber tire production was 899.108 million, an

increase of 10.8%. The bead wire in waste tires accounts for about 14% of the inner components of the bead. The pull-out test shows that the tensile strength of the industrial reclaimed steel wire is more than 1800 MPa, and the breaking force of the single wire is more than 3000 N, which is better than the ordinary wire rope. It can solve the problem of environmental pollution of waste tires and achieve the creative value of reusing waste materials.

And with reinforced concrete beam as one of the main force components of building structure, in the process of using and under the action of various environmental conditions, the material properties of structural components deteriorate over time [2]. In order to make the building meet the requirements of normal use, there are several

reinforcement methods commonly used in engineering: enlarging section reinforcement method [3], method of external packing-steel to strengthen [4], and strengthening with external prestressing [5, 6].

## 2. Research Background

At present, most of the domestic and foreign utilization of industrial reclaimed steel wire is to cut steel wire into steel fiber [7–10], but the method of using the overall length of steel wire is rarely seen. In 2000, Sun Hai et al. [11] analyzed 4 cases of exterior prestressed jumbled beam induced performance. At the same time, the application structure deformation derived the stiffness matrix, the PS curve conclusions were basically unified, and the rear component of the rear member was better. In 2004, Ghallab and Beeby [12] proposed an in vitro prestressed reinforced concrete beam calculation method, which is suitable for any load, and the calculation step is simple, and the calculation results are accurate compared with the test results and specifications. In 2005, Park et al. [13] conducted a loss of load capacity and dynamic response by the prestressed weight loss. The results show that the long-term loss of prestress is negligible, and the power response of the reinforcing bridge has no significant change, and the reinforcement makes the span deflection by 10% to 24%. In 2016, Denise Ferreira et al. [14] used the prestressed transverse reinforcement method to reinforce the shear strength of reinforced concrete beams and carried out finite element analysis. In order to explore the influence of unbonded external prestressing tendons on reinforced concrete beams, the shear-sensitive fiber beam formula is proposed. Through simulation and experimental verification, the shear performance enhancement of RC beam brought by different reinforcement schemes is obtained. In 2020, Khalaf and Al-Ahmed [15] proposed a test scheme of external prestressed steel strand reinforcement of large opening reinforced concrete deep beams, nine specimens were designed, and the failure tests were carried out under three-point bending. At present, the reinforcement materials for external prestressing are mostly prestressed steel bars, steel strands, and other materials, with lack of research on steel wire [16]. Therefore, based on the above considerations, the author combines the two to reinforce the concrete beam with the industrial recycled steel wire in the form of external prestressing, in order to explore the recycling way of waste tires solid resources, the performance of industrial reclaimed steel wire, and its influence on the reinforcement effect of concrete beam. In this experiment, a new strengthening with external prestressing technology is proposed. The industrial reclaimed steel wire is distributed and arranged at the bottom of the RC beam, and the saw tooth anchor is used at both ends to connect with the RC beam to make it a whole and work together. After the reinforcement test is completed, the bending static load test of the reinforced beam is carried out, and the test results are analyzed and discussed. It is expected to have a good role in promoting and theoretical support for subsequent research.

## 3. Materials

**3.1. Introduction of New Prestressed Steel Wire Anchor.** In the experiment, the distributed arrangement of steel wire is strengthened [17] at the bottom of RC beam by external prestressing, as shown in Figure 1. Under the action of prestress, the compressive stress is generated at the bottom of the beam in advance to resist part of the tensile stress generated at the bottom of the beam at the initial stage of loading, and the reinforcement effect is achieved. Because the diameter of industrial recycled steel wire is 1.5 mm, which is far less than the common prestressed steel bar or steel strand, the anchorage [18, 19] of steel bar or steel strand is not suitable for the steel wire used in this test. Based on this situation, our research group independently developed a new type of prestressed steel wire anchorage. The anchorage is steel, and its shape is designed as “saw tooth.” It can be applied to the anchoring work of such prestressed steel wire, reduces the prestress loss, and is easy to operate. It can realize the application of simple prestress without large prestressed tensioning equipment.

The size of the anchorage is 260 mm × 200 mm, and the total steel wire length is 1300 mm. The single anchorage has 10 bolts, and the middle 4 bolts are M12 high strength bolts, which clamp the steel wire in the tension stage. The outer four bolts are M16 high strength bolts, the length is 45 cm, and the role is to anchor the concrete beam [20, 21], so that it can work together. The middle two M16 bolts are chemical anchor bolts, which are directly implanted into the concrete beam through drilling and burying bolts, acting as fixed anchorage to avoid prestress loss caused by slippage of anchorage after force [22]. In order to make the steel wire have better anchoring effect, the contact surface between the steel wire and the anchor is designed as “serrated,” as shown in Figure 2.

Because the “saw tooth tip” is right angled and sharp, it is easy to produce stress concentration after clamping the steel wire, so that the steel wire is cut in advance. In order to prevent the occurrence of this phenomenon, a process is added in the design and production, and the “saw tooth tip” is changed to the chamfer with a radius of 3 mm, so that the steel wire can not only be reliable anchorage, but also avoid the risk of stress concentration.

**3.2. Design and Fabrication of Specimens.** Seven groups of reinforced concrete beams under different working conditions were made, including three groups of prestressed industrial recycled steel wire reinforced beams, three groups of prestressed ordinary steel wire rope reinforced contrast beams, and one group of unreinforced contrast beams. RC beams are rectangular section, section size is  $b \times h = 180 \text{ mm} \times 350 \text{ mm}$ , span is 1800 mm, the calculated span is 1500 mm. Concrete strength grade is C30, and concrete cover thickness is 30 mm. The specific parameters and reinforcement of the beam are shown in Table 1 and Figure 3.

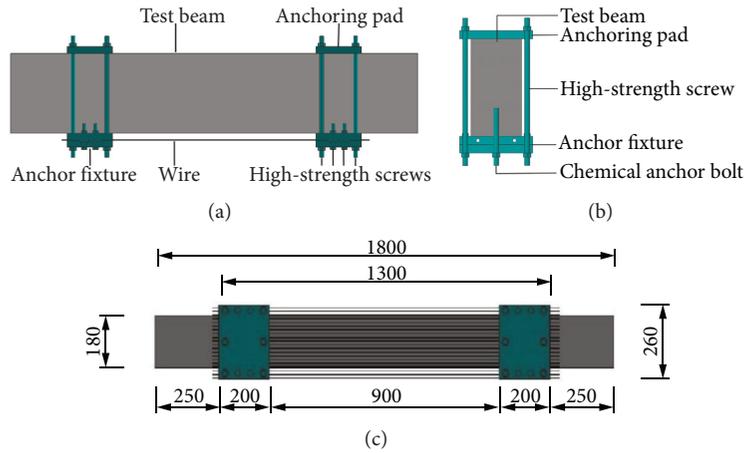


FIGURE 1: Specimen reinforcement diagram. (a) Front view. (b) Side view. (c) Bottom view.

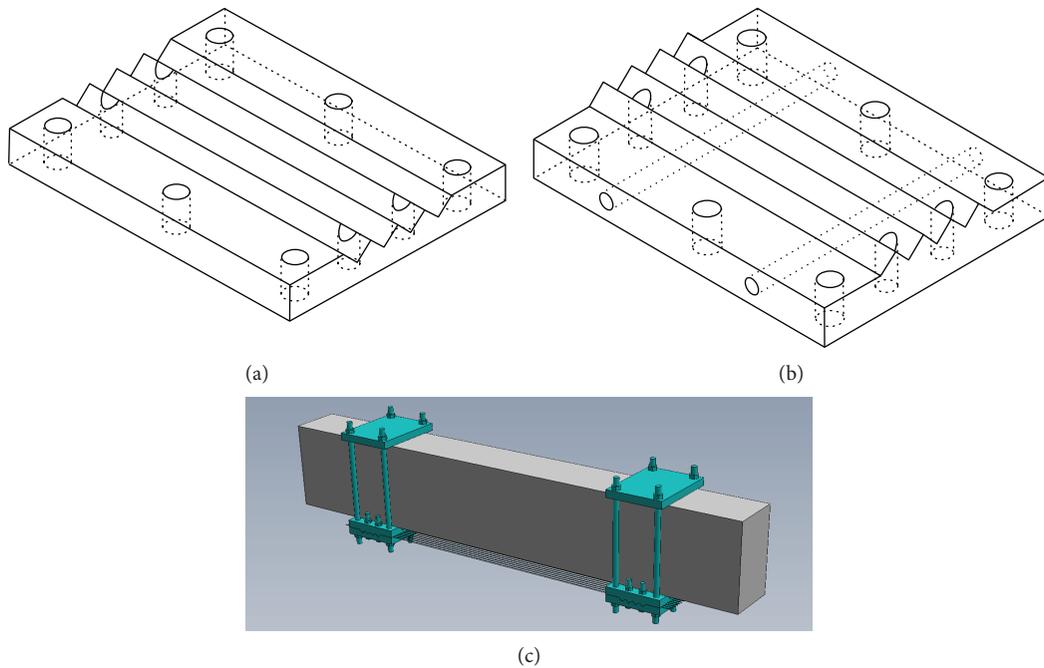


FIGURE 2: Anchorage detail. (a) Concave shape anchorage effect diagram. (b) Convex shape anchorage effect diagram. (c) Reinforcement effect diagram.

3.2.1. Test Materials

(1) *Mechanical Properties of Concrete.* In this experiment, the strength grade of concrete was designed as C30, and the mixture ratio was calculated according to the relevant research results [23]. Three groups of test blocks were made at the same time of pouring the specimen, and the size was 150 mm × 150 mm × 150 mm. The cube compressive test was carried out after 28 days of curing under the same conditions with the concrete specimen (Figure 4).

(2) *Industrial Reclaimed Steel Wire.* The industrial recycled steel wire used in this reinforcement test is a straight steel wire provided by Xinxiang Plastic Machinery Factory, Henan Province. After stripping from the tire and

grinding and rust removal, it can participate in the test. Steel wire diameter is 1.5 mm, and mass density is 7800 kg/m<sup>3</sup>.

(3) *Prestressed Ordinary Steel Wire Rope.* In order to explore the comparison of RC beam strengthened by industrial recycled steel wire and ordinary industrial steel wire, three groups of bending test of RC beam strengthened by prestressed ordinary steel wire rope were added. In order to ensure a single variable, the diameter of the wire rope selected in the test is the same as that of the industrial reclaimed steel wire, which is 1.5 mm. Steel wire parameters are shown in Table 2.

3.3. *Reinforcement Process.* The reinforcement work of this test is divided into two steps. First, the steel wire is stretched

TABLE 1: Table of specimen parameters.

Test specimen number	Type of reinforcement	Concrete grade	Diameter of tensile steel bar	Diameter of supplementary reinforcement	Diameter of stirrup	Diameter of wire	Prestress degree
CB-1	Comparison beam	C30	18 mm	12 mm	8 mm	—	—
PS-1	Prestressed steel wire rope	C30	18 mm	12 mm	8 mm	1.5 mm	30%
PS-2	Prestressed steel wire rope	C30	18 mm	12 mm	8 mm	1.5 mm	40%
PS-3	Prestressed steel wire rope	C30	18 mm	12 mm	8 mm	1.5 mm	50%
BW-1	Industrial reclaimed steel wire	C30	18 mm	12 mm	8 mm	1.5 mm	30%
BW-2	Industrial reclaimed steel wire	C30	18 mm	12 mm	8 mm	1.5 mm	40%
BW-3	Industrial reclaimed steel wire	C30	18 mm	12 mm	8 mm	1.5 mm	50%

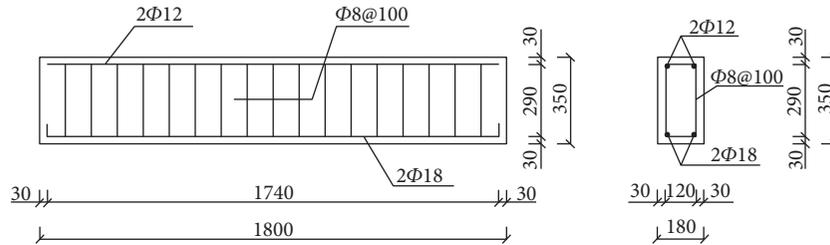


FIGURE 3: Reinforcement diagram of specimens.



FIGURE 4: Cube compressive test.

TABLE 2: Basic parameters of steel wire.

Type of steel wire	Diameter	Average length	Tensile strength	Density
Industrial reclaimed steel wire	1.5 mm	1800 mm	1800 Mpa	7800 kg/m <sup>3</sup>
Prestressed ordinary steel wire rope	1.5 mm	1800 mm	1470 Mpa	3200 kg/m <sup>3</sup>

to the prestressed state and then installed to the predetermined position at the bottom of the test beam to complete the reinforcement work. The steel wire is tensioned by a new type of prestressed tensioning device, as shown in Figure 5.

The main part of the device is two transmission frames, which are connected to four smooth screws at a specific position of the main transmission frame, and the auxiliary transmission frame is drilled at the corresponding position, so that the transmission frame can be connected to the main



FIGURE 5: Drawing of tension device.

body through the screws and can slide freely along the direction of the steel wire, which is convenient for the application of subsequent prestress. The anchorage is placed at both ends of the power transmission frames and fixed with M10 screws. Two jacks are placed symmetrically between the power transmission frames, and then the steel wire is arranged in a distributed manner, so that the jacks can be used to impose prestress on the steel wire.

The influence factors such as the arrangement, spacing, and jack position of the steel wire are focused to make the steel wire uniformly arranged and achieve the purpose of uniform stress. The specific steel wire number, spacing, and tension control stress of each specimen are shown in Table 3.

It is necessary to ensure that each steel wire is uniformly arranged, the spacing is consistent, and the steel wire is tightened to ensure uniform stress. Clamp the anchor and tighten the M12 bolts immediately after the wire is arranged to prevent the wire from shifting. Then check whether the jack position is symmetrical or not, and start tension after confirmation.

The tension jack adopts two 30-ton hydraulic jacks, and the values of each jack are consistent. When the ideal value is reached, the tension is completed. At this time, the prepared M30 double-headed bolt is needed to replace the jack. The component is composed of two M30 high strength bolts with a length of 8 cm connected to a connecting nut with a length of 8 cm. Its function is to rotate the connecting nut in the middle to extend the bolts at both ends outward and place them in the middle of the two jacks. The screw nut can replace the jack so that it is easy to install it to the bottom of the concrete beam.

At the bottom of RC beam to be strengthened, the hole diameter is 18 mm and the hole depth is 100 mm. After the hole is formed, the ash inside the hole is removed to ensure the cleaning of the hole, so as to ensure the embedding effect. The chemical medicinal water was placed in the hole, and the medicinal water was smashed with anchor bolt and quickly rotated and stirred to ensure that the medicinal water was uniformly smeared on the anchor bolt. After placing the anchor at an appropriate depth, adjust the anchor to ensure verticality, and then stand for 2 hours until the chemical fully reacts to ensure that the anchor reaches the intended strength.

The anchor bolt corresponding to the anchorage and its hole position was adjusted to align and penetrate. After the anchorage was fully fitted to the bottom of RC beam, the chemical anchor bolt nut was tightened, and the 45 cm long screw and steel plate were anchored at the top of RC beam to tighten the nut. Check the nuts with or without signs of loosening, and remove the transmission frame after confirmation. The reinforcement is completed as shown in Figure 6.

## 4. Experimental Programs

### 4.1. Loading Device and Loading System

**4.1.1. Loading Device.** The experiment was conducted in the structural laboratory of the civil teaching building of Jilin Jianzhu University in Changchun City, Jilin Province. The 500 kN electrohydraulic servo universal testing machine is used for loading. The loading device is shown in Figure 7, including pedestal, bearing, distribution beam, and actuator.

**4.1.2. Loading System.** The bending test adopts static loading method. In order to obtain better test results, the test is divided into two stages: preloading and formal loading.

After the test device is ready, the 2 kN/s preloading is carried out to eliminate the bad contact and virtual displacement of the loading system and ensure that the loading equipment and measurement equipment can work normally.

In the formal loading stage, force control is used for loading. Loaded at 5 kN level at the beginning of the test, before and after the specimen reaches the cracking load and yield load, in order to accurately observe, it is adjusted to 3 kN level for loading. After the tensile steel bar yields, 5 kN level is used to continue loading until the specimen is completely destroyed.

**4.2. Test Situation.** The specimen is mainly divided into three stages in the stress process, namely, elastic stage, crack working stage, and failure stage. Concrete is elastic stage from the beginning of loading to cracking load. At this time, the stiffness of the component is large, the deflection is small, and there is no crack. The load and deflection are basically linear.

The working stage with cracks means that after the first crack appears in the concrete member, the member enters the plastic state from the elastic state, and the concrete in the tensile zone gradually withdraws from work due to the loss of bearing capacity, and the tensile stress is all borne by the tensile reinforcement. At this time, with the increase of load, the tensile area of concrete members continues to expand, the number of cracks continues to increase, and the strain of tensile reinforcement and the deflection growth rate of members continue to accelerate.

When the load increases to a certain value, the tensile reinforcement begins to yield, and the cracks continue to extend upward and widen, which declares that the component enters the failure stage. With the continuous loading, the deflection increases rapidly, the concrete in the compression zone is crushed, and the section stiffness further decreases. At this time, the beam has been destroyed.

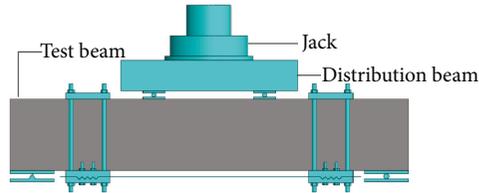
In this experiment, with the increase of load, the tensile reinforcement at the bottom of the beam yielded, and the deflection increased rapidly. The concrete in the compression zone began to be crushed, resulting in spalling. And the steel wire at the bottom of the reinforced beam still bears large tensile stress and still has bearing capacity after the yield of the tensile reinforcement. With the increase of load, the test ends. There is no failure of prestressed steel wire anchor and steel

TABLE 3: Reinforcement parameter table.

Test specimen number	Type of reinforcement	Diameter	Number of reinforcements	Steel wire spacing	Tension control stress
CB-1	Comparison beam	—	—	—	—
PS-1	Prestressed steel wire rope	1.5 mm	20	8 mm	15.6 kN
PS-2	Prestressed steel wire rope	1.5 mm	20	8 mm	20.8 kN
PS-3	Prestressed steel wire rope	1.5 mm	20	8 mm	26.1 kN
BW-1	Industrial reclaimed steel wire	1.5 mm	20	8 mm	19.1 kN
BW-2	Industrial reclaimed steel wire	1.5 mm	20	8 mm	25.5 kN
BW-3	Industrial reclaimed steel wire	1.5 mm	20	8 mm	31.9 kN



FIGURE 6: Complete reinforcement.



(a)



(b)

FIGURE 7: Loading device diagram. (a) Loading device. (b) Loading photo.

wire loosening in the test. The new anchor can complete the work of anchoring steel wire and has certain reliability as shown in Figure 8.

**4.3. Test Data Results.** Table 4 is the summary of the main test results of 30%, 40%, and 50% industrial recycled steel wire reinforced beams, steel wire rope reinforced beams, and unreinforced beams.

#### 4.4. Comparison of Experimental Results

**4.4.1. Comparison of Test Results of Reinforced and Unreinforced Beams.** Compared with the strengthened beam and the unstrengthened beam, the load at first crack and limit load of the unstrengthened beam under the same conditions are 46.77 kN and 182.44 kN, respectively, and the maximum vertical displacement at mid-span is 49 mm when the beam is damaged. The load at first crack of the reinforced beam with rectangular steel wire rope is 54.26 kN, the limit load is 258.37 kN, and the maximum vertical displacement in the middle span is 39 mm. After the beam is strengthened by steel wire rope with external prestressing, the load at first crack increases by 16.01%, the ultimate load increases by 17.45%, the load at first crack and limit load of the reinforced beam with the same degree of 30% were 58.73 kN and



FIGURE 8: Failure diagram of specimens

264.74 kN, respectively, and the maximum vertical displacement at mid-span was 31 mm. The stiffness and bearing capacity of the beam are greatly improved after strengthening with external prestressing by industrial recycled steel wire. The load at first crack is increased by 25.57%, and the ultimate load is increased by 20.34%. In addition, the strain of reinforced RC beams, whether before or after cracking, even to the ultimate failure stage, has also been greatly improved. The main reason is that the external prestressing force of RC beam changes its mechanical characteristics. The antibending moment provided by prestressed industrial recycled steel wire at the bottom of the beam largely offsets the self-weight and external load and improves the cracking load and ultimate bearing capacity of the beam.

TABLE 4: Test result.

Test specimen number	Type of reinforcement	Load at first crack	Yield load	Limit load	Limit deflection	Failure condition
CB-1	Comparison beam	46.77 kN	182.44 kN	219.99 kN	49 mm	Longitudinal reinforcement yield
PS-1	Prestressed steel wire rope	54.26 kN	235.17 kN	258.37 kN	39 mm	Wire rope broken
PS-2	Prestressed steel wire rope	57.81 kN	244.36 kN	269.53 kN	52 mm	Wire rope broken
PS-3	Prestressed steel wire rope	60.22 kN	248.77 kN	278.16 kN	60 mm	Wire rope broken, larger deflection
BW-1	Industrial reclaimed steel wire	58.73 kN	246.61 kN	264.74 kN	31 mm	Partial broken of industrial recycled steel wire
BW-2	Industrial reclaimed steel wire	61.75 kN	252.19 kN	279.81 kN	45 mm	Industrial recycled steel wire broken
BW-3	Industrial reclaimed steel wire	68.88 kN	255.48 kN	309.64 kN	52 mm	Industrial recycled steel wire broken, large deflection

4.4.2. Comparison of Test Result of Reinforced Beams with Different Prestress Degree. When the reinforcement method is certain, with the increase of the degree, the load at first crack and limit load of the reinforced beam with rectangular steel wire rope increase. Load at first crack increased by 7.59% and 5.15%, and limit load increased by 5.07% and 3.92%, respectively. And the load at first crack and limit load of the beam strengthened with industrial recycled steel wire increased, the load at first crack increased by 7.59% and 15.24%, and the limit load increased by 6.85% and 13.56%. It shows that the larger degree of prestress is beneficial to give full play to the reinforcement effect, and the industrial recycled steel wire reinforcement effect is better.

5. Analysis of Test Results

5.1. Analysis of Flexural Capacity. At the beginning of the test, the curves of all specimens increased steadily in the oblique straight line state. Because the specimens are in elastic state, the stiffness difference is not big, but the effect of industrial recycled steel wire on the stiffness of the specimen can still be seen. With the continuous improvement of the load, the superiority of reinforced beams began to show. We can clearly and intuitively see the different bearing capacity of each specimen. At the same time, compared with the prestressed steel wire rope reinforced specimens (PS-1~3 group) and the industrial recycled steel wire rope reinforced specimens (BW-1~3 group), it can be analyzed that the industrial reclaimed steel wire is more obvious than the prestressed steel wire rope to improve the flexural capacity of RC beams. Next, we will analyze the load at first crack, yield load, and limit load one by one.

5.1.1. Load at First Crack. The load at first crack is the load value of the specimen from the beginning of loading until the first crack occurs. The load at first crack of seven groups of specimens is shown in Figure 9. The load at first crack of CB-1 group specimens without prestressed reinforcement is 46.77 kN, and the six groups of specimens are all reinforced beams. The load at first crack of CB-1 group specimens has different degrees of improvement compared with the contrast beams. With the increase of prestress, the industrial recycled steel wire has a positive impact on restricting the

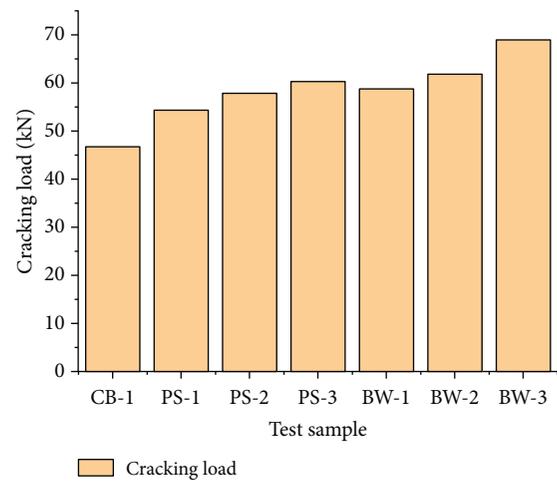


FIGURE 9: Specimens load at first crack.

crack development of components. Compared with the RC beam strengthened with prestressed steel wire rope, the load at first crack of the RC beam strengthened with industrial recycled steel wire rope is more obvious than that of the RC beam strengthened with ordinary prestressed steel wire rope.

5.1.2. Yield Load. The yield load is the turning point of the specimen from the working stage with cracks to the failure stage. When the member reaches the yield load, the main reinforcement yields and the concrete in the compression zone is crushed. Among the seven groups of specimens, the yield load of the contrast beam was the lowest, and its yield load was 182.44 kN. The highest yield load was 50% prestressed industrial reclaimed steel wire reinforced beam, and its yield load was 255.48 kN, a total of 40.04% increase. The 50% rolled steel wire rope reinforced beam was 36.36% higher than the contrast beam. It can be seen from Figure 10 that the yield strength of the strengthened beam is indeed greatly improved than that of the contrast beam. For this test, according to the different reinforcement materials and the degree of prestress, the yield strength is increased by 28.90%~40.04%, but with the increase of the degree of prestress, the yield load value is not greatly improved. Under the same

degree of prestress, the yield load of the beam reinforced by industrial recycled steel wire is significantly higher than that of the beam reinforced by prestressed steel wire rope, which once again shows the superiority of the performance of industrial recycled steel wire.

**5.1.3. Limit Load.** When the specimen reaches limit load, it indicates that it has reached the ultimate state of bearing capacity, and the test is terminated immediately. The ultimate bearing capacity of the contrast beam CB-1 is 219.99 kN, and the ultimate bearing capacity of the reinforced beam is greatly improved compared with the contrast beam. Due to the effect of reinforcement materials and prestress, after the yield load is reached, the reinforced steel wire rope or industrial reinforced steel wire can continue to withstand tensile stress until it is broken, so the bearing capacity loss rate of the reinforced beam is much slower than that of the contrast beam. The limit load comparison of the strengthened beam is shown in Figure 11.

The above data show that the seven groups of experiments have achieved good results, which can play a comparative role. The flexural capacity of the six groups of strengthened beams has been greatly improved, and the prestressed steel wire rope or steel strand can greatly help the load at first crack, yield load, and limit load of reinforced concrete members. Based on the analysis of this paper, the reinforcement effect is the best when the prestressed degree is 50%. In the test process, when the component reaches the yield load, the fracture rate of the prestressed steel wire rope is much faster than that of the industrial recycled steel wire, and its tensile properties and ductility are inferior to those of the industrial recycled steel wire. Combined with the experimental data, it can be proved. The strengthening effect of industrial recycled steel wire for RC beam bending performance is better than that of prestressed steel wire rope.

**5.2. Fracture Analysis.** Figures 12 to 18 recorded the crack development of each group of specimens after loading, and the crack width increased with the increase of load. The number of cracks tended to be stable at the late loading stage, and the number of cracks no longer increased. Several main cracks continued to extend upward with the increase of load, and the width increased until the specimen was destroyed.

Combined with the crack conditions and test phenomena shown in the above figures, we can analyze the following:

After load at first crack, the number of cracks in each specimen increased continuously. With the increase of load, 2–3 main cracks gradually formed in the pure bending section. Loaded to about 160 kN, pure bending section no longer shows new cracks, and the original cracks continue to extend upward. The mid-span cracks, especially the main cracks, are mostly vertical upward, while in the prestressed steel wire anchor, oblique cracks develop to the mid-span area. This is because the concrete at the anchorage is in a tensile state when prestress is

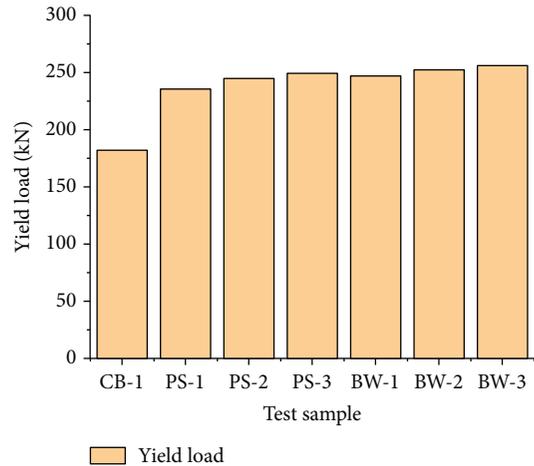


FIGURE 10: Yield load of specimens.

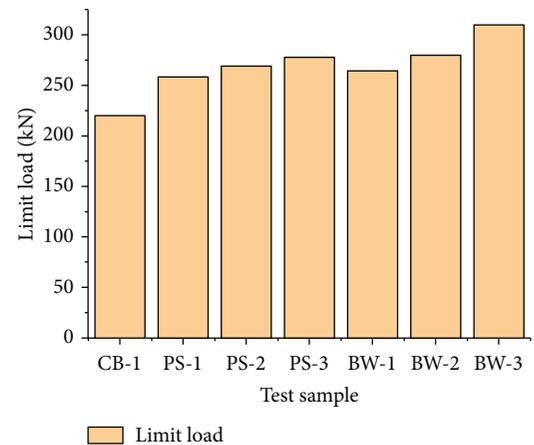


FIGURE 11: Specimens limit load.

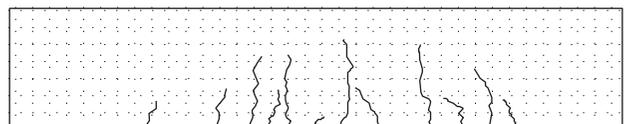


FIGURE 12: Comparison of cracks in beams.

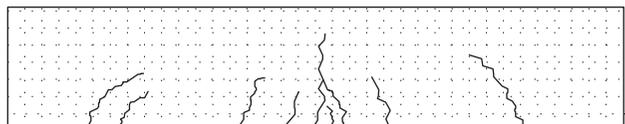


FIGURE 13: PS-1 group specimen cracks.

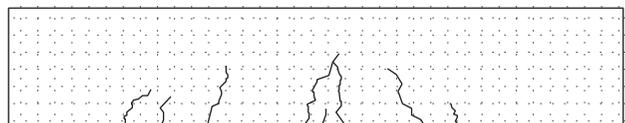


FIGURE 14: PS-2 specimen cracks.

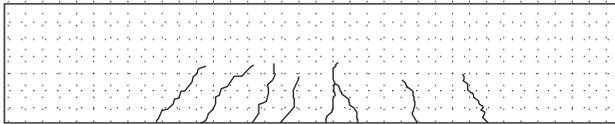


FIGURE 15: PS-3 specimen cracks.

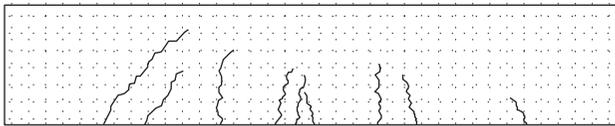


FIGURE 16: BW-1 specimen cracks.

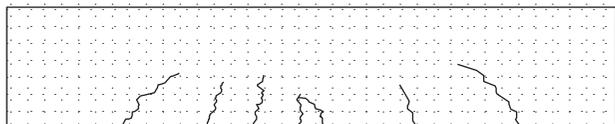


FIGURE 17: BW-2 specimen cracks.

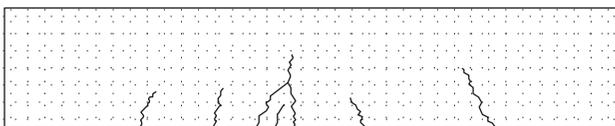


FIGURE 18: BW-3 specimen cracks.

applied, and the tensile force is increasing after loading, resulting in oblique cracks.

The experimental results show that the specimens with different prestress degrees show different cracks. Firstly, the load at first crack of the reinforced beam is significantly higher than that of the contrast beam; secondly, due to the effect of prestress, the number of cracks and crack development speed of the reinforced beam are better than those of the contrast beam. At the same time, the data show that the specimen with high prestress has better cracking performance, indicating that the reinforcement of prestressed industrial recycled steel wire has effective crack resistance, which is a good supplement to the shortcomings of low tensile strength of concrete [24].

**5.3. Mid-Span Deflection Analysis.** Through the collation and analysis of seven groups of test data, the load-deflection curve is obtained as shown in Figure 19.

It can be seen from Figures 5–9 and 19 that the deflections of the seven groups of specimens increase gradually with the loading. From the beginning of the test to the load at first crack, the deflections of all the specimens showed a trend of oblique linear growth, and the slopes were basically the same. The slope of the rising section of the reinforced beam curve was large, which proved that the prestress had brought effective improvement to the deflection of the RC beam. When the specimen reaches yield load, the load-deflection curve turns, and the load growth slows down while the

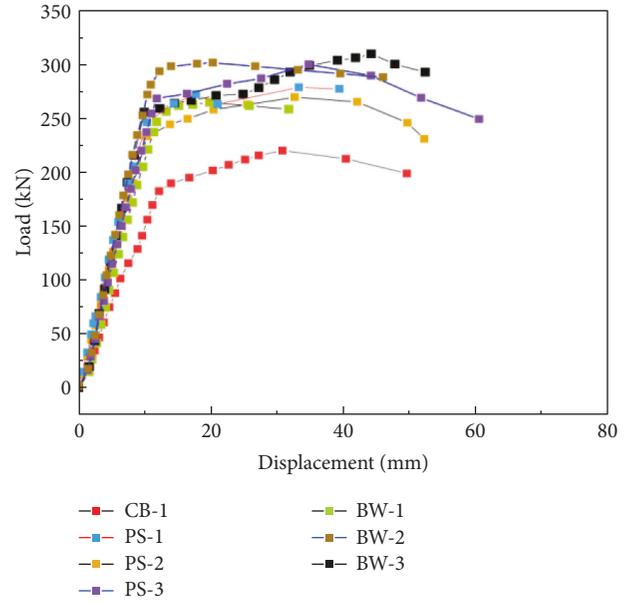


FIGURE 19: Load-deflection curve.

deflection increases rapidly. When the specimen reaches the ultimate bearing capacity, the load is no longer increased, and the deflection increases faster, leading to the termination of the test.

It can be seen from the figure that, after the load at first crack of the comparison beam, the load-deflection curve began to separate from the reinforced beam, and the deflection growth rate became faster. After the load reaches 182.44 kN, the main reinforcement of the contrast beam has yielded, and the load-deflection curve of the reinforced beam still increases linearly. At the same time, the load of the contrast beam has a significant sudden drop after reaching the limit load, and there is no such phenomenon in the reinforced beam. Even if the main reinforcement has yielded, the loss of its bearing capacity is relatively slow due to the reinforcement effect of steel wire, indicating that prestressed reinforcement has significantly improved the stiffness and ductility of RC beam.

Under the same load, the deflection of the same prestressed industrial recycled steel wire reinforced beam is significantly less than that of the prestressed steel wire rope reinforced beam, namely, PS-1 > BW-1. The prestressed degrees of BW-1, BW-2, and BW-3 of the three groups of prestressed industrial recycled steel wire reinforced beams are 30%, 40%, and 50%, respectively. Under the same load, the deflection size is BW-1 > BW-2 > BW-3, indicating that, with the increase of prestress, the mid-span deflection of the reinforced beam decreases and the stiffness of the reinforced beam increases.

## 6. Numerical Simulation Analysis

**6.1. Establishment of Finite Element Model 00.** In order to further explore the mechanical properties of industrial recycled steel wire reinforced with external prestressed beams under

different prestress, four groups of specimens were designed in this simulation, including one group of contrast beams and three groups of prestressed industrial recycled steel wire reinforced beams. In order to restore the test as far as possible, the size of the simulated specimen is the same as that of the test specimen, and the concrete strength grade is C30. Specimen and material parameters are shown in Table 5 and Table 6.

In the process of ABAQUS modeling, the concrete element type is modeled by solid C3D8 element and the steel bar is modeled by truss C3D2 element. In order to ensure the accuracy of simulation, industrial recycled steel wire is simulated by solid element. In order to prevent the local stress concentration in the process of stress, a steel plate with the size of 100 mm × 180 mm × 40 mm is set at the bearing and the stress point, and the parameters of the steel plate are standard steel parameters [25].

The modeling is shown in Figure 20.

**6.2. Interaction and Boundary Conditions.** In the simulation process, the embedding technology is first used to embed the steel skeleton into the concrete specimen to simulate the relationship between steel and concrete in practical engineering, so as to ensure that the steel and concrete can work together. Prestressed steel wire anchor with the size of 100 mm × 180 mm × 60 mm steel block simulation, the contact between the stress point and the bearing steel plate, and the simulation anchor steel block and concrete are tie constraints. Because there is no slip between the steel wire and the anchor during the test, the steel wire and the anchor are bound together with tie constraints. The main surface is the anchor, and the cross section of the industrial recycled steel wire is selected from the surface.

In order to restore the test, the two-point loading is still selected in this simulation. The loading point is at the same position as the test beam, which is the three points along the span of the test beam. To ensure accurate calculation, the loading point should not be set directly on the concrete beam. In this simulation, a RP point is set at the outer surface center of the steel plate at the bearing and the stress point, which is coupled with the steel plate. The boundary conditions and load are set on the RP point. The simulated concrete beam is a simply supported beam, and the two ends of the support are set as one end fixed hinge support and the other end sliding hinge support, so the boundary conditions of the steel plate at both ends are set as  $U1 = 0, U2 = 0, U3 = 0, UR2 = 0, UR3 = 0; u1 = 0, U2 = 0, UR2 = 0, UR3 = 0$ .

**6.3. Grid Division.** At the same time to meet the requirements of accuracy and speed, the simulation of concrete beam mesh size is set to 30 mm, pure bending section is the key part of the bending beam, so we encrypt the pure bending section of the grid, and the size is set to 20 mm. The mesh size of steel skeleton and industrial reclaimed steel wire is set to 20 mm. The grid division is shown in Figure 21.

**6.4. Application of Prestress.** In this paper, the temperature reduction method is used to simulate the prestressing of

industrial reclaimed steel wire [26]. Based on the characteristics of steel wire thermal expansion and contraction, a predefined field is first applied to the steel wire for cooling treatment. After cooling, the steel wire will contract. This contraction phenomenon is limited to produce tensile stress on the anchorage, so that the tensile area of concrete is subjected to compressive stress first. This compressive stress can offset part of the bending moment in the initial stage of loading, and the reinforcement effect is achieved. In the temperature reduction method, the calculation of temperature change value is determined by formula

$$\Delta T = \frac{\sigma}{\alpha EA}. \quad (1)$$

In the formula,  $\Delta T$  is the temperature change value;  $\sigma$  represents the prestress value to be applied;  $E$  represents elastic modulus of industrial reclaimed steel wire;  $\alpha$  represents the temperature expansion coefficient of industrial reclaimed steel wire, which is  $1 \times 10^{-5}$  in this paper; and  $A$  represents the cross-sectional area of industrial reclaimed steel wire.

The specific step of the temperature reduction method is to first set a predefined field at initial, the area is all industrial recycled steel wire, the category is temperature, and the initial temperature is set to 0. Then the predefined field is set in Step 1, and the temperature is set to simulate the required cooling value. After the operation, the prestress of the industrial reclaimed steel wire can be applied.

This simulation of the reinforcement beam a total of 3 are using prestressed industrial recycled steel wire reinforcement. The degree of prestress is 30%, 40%, and 50%, respectively. The specific value of temperature reduction method is shown in Table 7, and the stress nephogram after prestress is shown in Figure 22.

The above figure is the stress nephogram of industrial reclaimed steel wire and concrete after prestressing. At this time, the stress of the industrial reclaimed steel wire has reached the target prestress value, and the longitudinal bars at the bottom of the concrete and the bottom of the beam have produced prestress. The prestress values of each component of the three groups of specimens are shown in Table 8.

Step 1 is a predefined temperature field, and its cooling value is transferred to Step 2. The displacement load is applied on Step 2, and the load is applied on the RP point at the stress point. The displacement values of the two points are the same, and the static loading of RC beam is carried out by establishing the law of amplitude. After the above process is completed, the data of this model is checked, and the work is submitted to calculate.

**6.5. Finite Element Simulation Results and Analysis Comparison.** Figure 23 is the stress nephogram of the specimen after loading. The bending bearing capacity and plastic damage of the specimen are studied and analyzed. The specimens of different working conditions are compared, and the influence of different prestress degree on the

TABLE 5: Table of specimen parameter.

Test specimen number	Type of reinforcement	Concrete grades	Diameter of tensile steel bar	Diameter of supplementary reinforcement	Diameter of wire	Number of reinforcements	Prestressed degree	Control stress for tensioning
CB-1	Comparison beam	C30	18 mm	12 mm	—	—	—	—
BW-1	Strengthened beam	C30	18 mm	12 mm	1.5 mm	20	30%	486 Mpa
BW-2	Strengthened beam	C30	18 mm	12 mm	1.5 mm	20	40%	648 Mpa
BW-3	Strengthened beam	C30	18 mm	12 mm	1.5 mm	20	50%	810 Mpa

TABLE 6: Table of material parameter.

Category	Density	Elastic modulus	Yield strength	Poisson's ratio
Concrete	2400 kg/m <sup>3</sup>	30G pa	—	0.2
Steel bar	7800 kg/m <sup>3</sup>	200 Gpa	400 Mpa	0.3
Industrial reclaimed steel wire	7800 kg/m <sup>3</sup>	200 Gpa	1800 Mpa	0.3

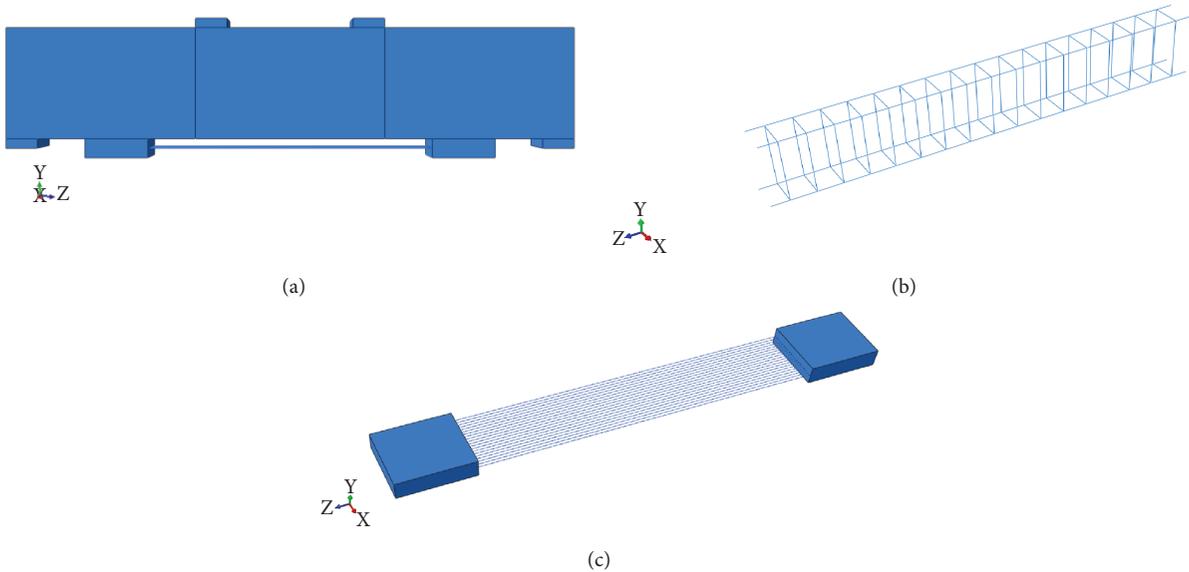


FIGURE 20: Modeling example. (a) 3D model of specimen. (b) 3D model of steel skeleton. (c) Reinforcement device.

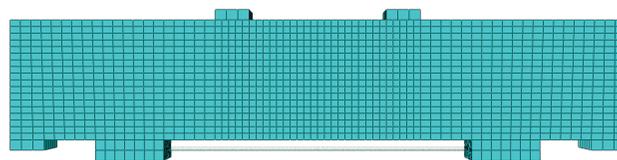


FIGURE 21: Grid partition graph.

bending effect of steel wire reinforced beam is analyzed. Compared with the experimental results, the validity of the simulation is verified.

6.5.1. *Analysis of Flexural Capacity.* Figure 24 shows the comparison between the simulation results and the test results of each group of specimens. It can be seen from the

figure that the deviation between the simulation value and the test value is within 10%. Therefore, in general, the simulation beam is in good agreement with the test beam, indicating that the bending test simulation can better simulate the mechanical properties of each group of specimens.

Figure 25 shows the comparison of load-displacement curves of simulated beams with different degrees of

TABLE 7: Numerical table of temperature reduction method.

Number of reinforcements	Number of reinforcements	Prestressed degree (%)	Target prestress value	Target prestress value
BW-1	20	30	486 Mpa	134°C
BW-2	20	40	648 Mpa	179°C
BW-3	20	50	810 Mpa	223°C

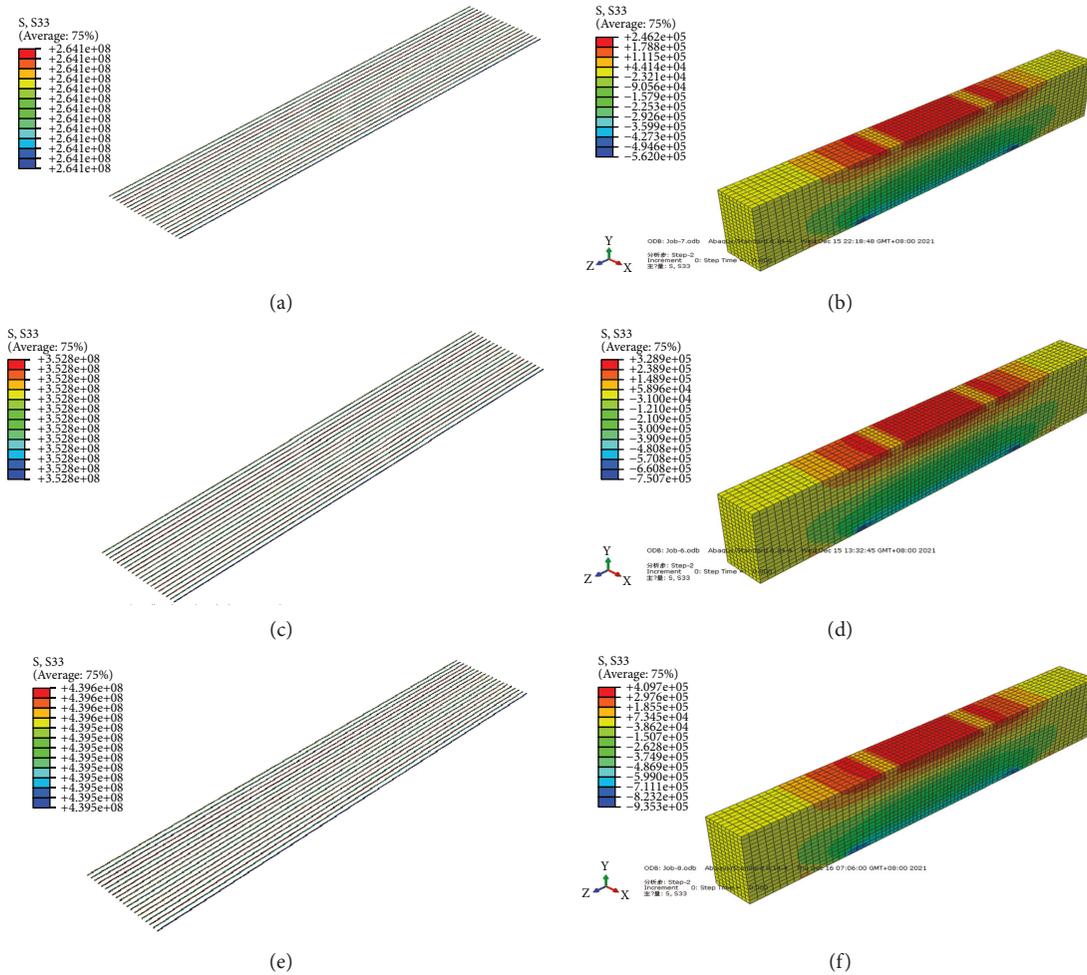


FIGURE 22: Parts cloud chart after prestressing. (a) 30% prestress industrial reclaimed steel wire. (b) 30% prestress RC beam. (c) 40% prestress industrial reclaimed steel wire. (d) 40% prestress RC beam. (e) 50% prestress industrial reclaimed steel wire. (f) 50% prestress RC beam.

TABLE 8: Actual prestress values of each specimen.

Number of reinforcements	Prestressed degree	Industrial reclaimed steel wire	Concrete beam	Longitudinal steel bar
BW-1	30%	487 Mpa	1.6 Mpa	5.8 Mpa
BW-2	40%	652 Mpa	2.2 Mpa	7.2 Mpa
BW-3	50%	817 Mpa	3.5 Mpa	9.9 Mpa

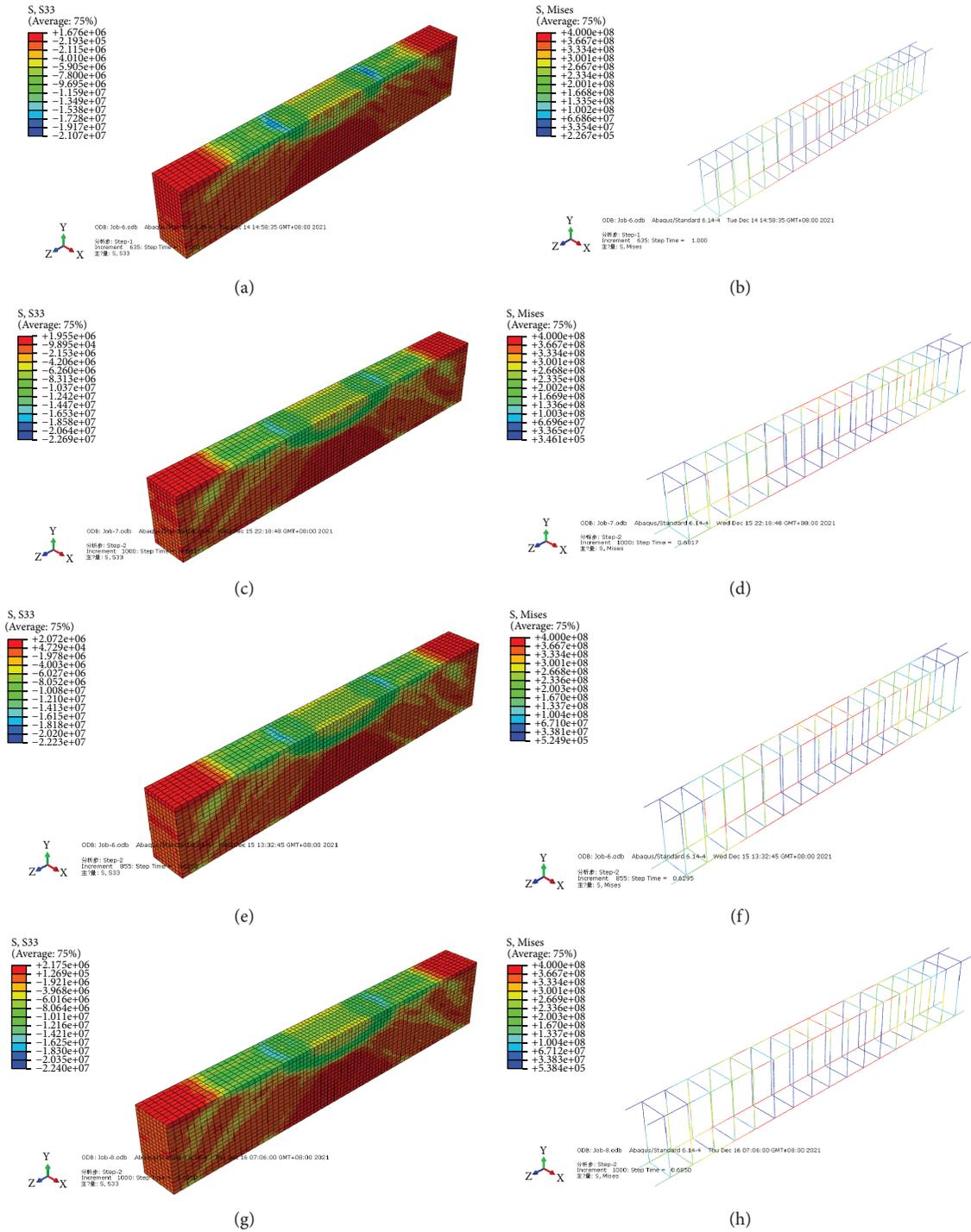


FIGURE 23: Stress nephogram of specimen. (a) Comparison beam. (b) 30% prestress industrial reclaimed steel wire strengthened beam. (c) Stress nephogram of group BW-1 concrete. (d) Steel skeleton stress nephogram of BW-1 group. (e) Stress nephogram of group BW-2 concrete. (f) Steel skeleton stress nephogram of BW-2 group. (g) Stress nephogram of group BW-3 concrete. (h) Steel skeleton stress nephogram of BW-3 group.

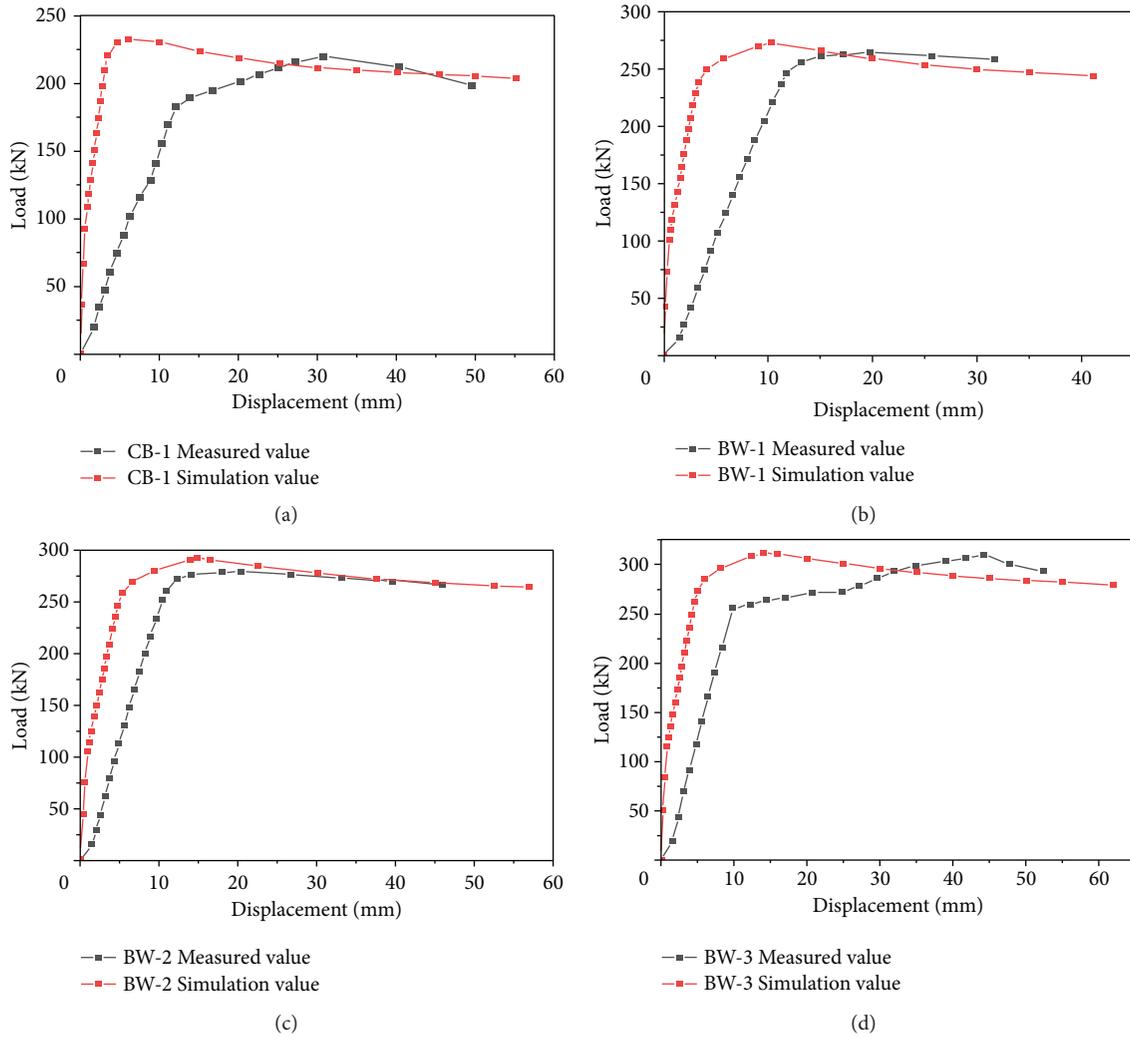


FIGURE 24: Comparison of load-displacement curves between simulated and measured value. (a) Comparison beam. (b) 30% prestress industrial reclaimed steel wire strengthened beam. (c) 40% prestress industrial reclaimed steel wire strengthened beam. (d) 50% prestress industrial reclaimed steel wire strengthened beam.

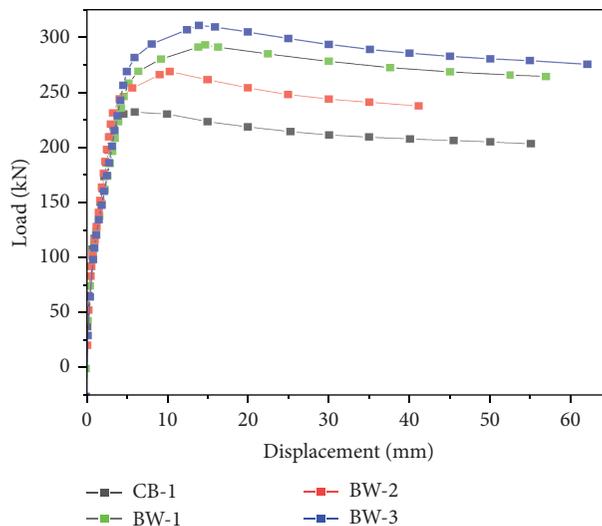


FIGURE 25: Comparison of load-displacement curves of simulated beams.

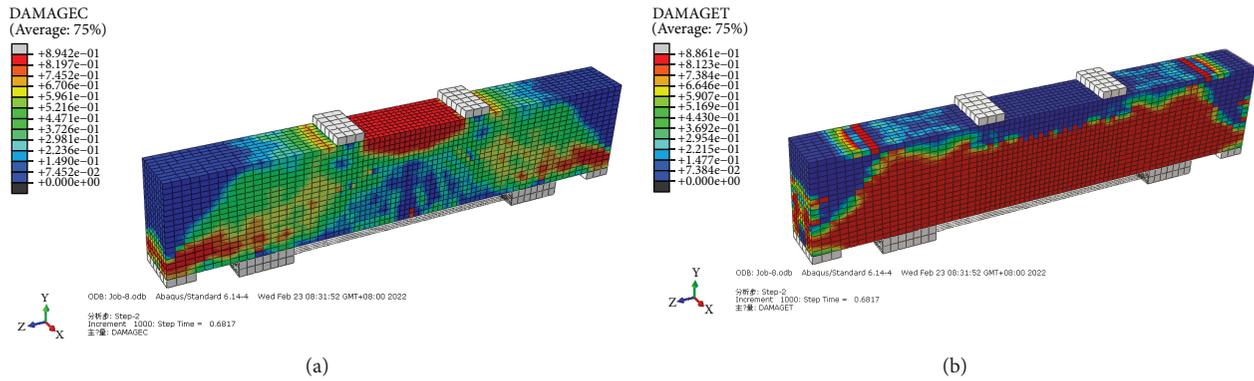


FIGURE 26: Damage nephogram of BW-1 group. (a) Compression damage nephogram of BW-1 group. (b) Tensile damage nephogram of BW-1 group.

prestress. It can be clearly seen that, compared with the contrast beam, the bending ultimate bearing capacity of RC beam is greatly improved by industrial recycled steel wire. Compared with the control beam, the BW-1 specimen increased by 17.48%, and the BW-2 and BW-3 specimens increased by 26.40% and 35.52%, respectively. It can be seen that, for the reinforced specimens with different degrees, the greater the degree is, the better the reinforcement effect of RC beam is.

**6.5.2. Damage Analysis of Concrete.** In this simulation, the plastic damage model of concrete can be used to observe and analyze the damage of concrete by DAMAGEC and DAMAGET. By comparing the failure mode of the specimen in the test, it can be found that the failure area of the two is close, which verifies the effectiveness of the simulation.

In Figure 26, the compressive damage of concrete beams mainly occurs in the central region of the pure bending section of the compression zone and near the loading point. The tensile damage mainly occurs in the middle of the pure bending section and near the anchorage point. The tensile damage of the finite element model is relatively serious at the anchorage point, while only 1–2 slight cracks appear at the anchorage point in the test, and the damage phenomenon is consistent with that in the test.

## 7. Conclusions

Through the research and analysis of bending static load test of seven groups of RC beams under different working conditions, the following conclusions can be obtained:

- (1) Compared with the externally prestressed reinforced beam and the unreinforced beam, the cracking load and ultimate load of the externally prestressed steel wire rope reinforced beam under the same conditions increase slightly. The stiffness and bearing capacity of beams strengthened with industrial recycled steel wire with the same prestress degree are greatly improved, and the cracking load and ultimate load are significantly improved. External prestressed reinforcement improves the cracking load and ultimate bearing capacity of the beam.

- (2) When the reinforcement method is certain, with the increase of prestress degree, the cracking load and ultimate load of prestressed steel wire rope reinforced beam increase. The cracking load and ultimate load of the beam strengthened with industrial recycled steel wire increase, and the effect is more obvious. It shows that the increase of prestress can effectively improve the bearing capacity of flexural members, and the reinforcement effect of industrial recycled steel wire is better than that of ordinary prestressed steel wire rope.
- (3) Industrial recycled steel wire has a positive effect on deflection, crack resistance, and deformation of flexural members. In particular the crack development of flexural members has a good inhibitory effect. With the increase of the degree of prestress, the number of cracks decreases when the specimen is damaged, indicating that the industrial recycled steel wire can play a good role in strengthening the flexural members.
- (4) ABAQUS finite element simulation software was used to simulate the comparison beam and the reinforced steel wire reinforced beam, and the simulation results were obtained and compared with the test results. The results show that the experimental values are in good agreement with the simulation values, which further verifies the reliability of the test.

## Data Availability

All the raw data used to support the findings of this study are included within the article. All the raw data are available from the corresponding author upon request.

## Conflicts of Interest

The authors declare no conflicts of interest.

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