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Research Article

Studies on the RC Beam Strengthened by Using the Exterior-Wrapping U-Shaped Steel Plate and Its Application

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Based on practical frame structures, constructional methods of the reinforced concrete (RC) frame beam strengthened by using an exterior-wrapping U-shaped steel plate are introduced. With reference to the *code for design of strengthening concrete structure*, the bearing capacity formula of the RC frame beams strengthened by using the exterior-wrapping U-shaped steel plate is briefly derived. After that, the finite element analysis of the frame beam before and after the reinforcement of the engineering example is carried out through ABAQUS software, and the results of the analysis of the bearing capacity are compared with the calculation results of the theoretical formula. At the same time, through comparing and analysing the U-shaped steel plate strengthening method and the "angle steel + batten plate" strengthening method, the result that the RC beam strengthened by using the exterior-wrapping U-shaped steel plate has better mechanical performance is drawn. Finally, the application of the exterior-wrapping U-shaped steel plate strengthening method is rationally suggested.

1. Introduction

At present, China's reinforcement technology has become increasingly mature, with complete reinforcement technical regulations and design codes including *technical specification for seismic strengthening of buildings* (JGJ 116-2009) [1] and *code for design of strengthening concrete structure* (GB 50367-2013) [2]. The above codes and literature [3, 4] introduced common reinforcement methods of concrete frame beams, such as structure member strengthening with externally wrapped U-shaped steel, pasted steel plate, increasing section area, concrete replacement, pasted FRP, prestressed CFRP plates, prestressed wire rope mesh and polymer modified cement mortar layer, and wire wrapped. Among them, structure member strengthening with externally wrapped U-shaped steel is the most traditional and the most mature reinforcement method with the advantage of fast construction speed, which is applicable to the reinforcement of concrete members that need to improve the bearing capacity greatly without increasing the section size. The concrete beam strengthening methods described in the literature [5–9] are basically the same, generally consistent with the codes, that is, the strengthening method of "angle steel + batten plate (also known as hoop plate)," as shown in Figure 1. This paper introduces the method of the strengthening RC frame beam by using the exterior-wrapping U-shaped steel plate. Compared with the above methods, it has the characteristics of greater bearing capacity, smaller effect on section size and appearance, and simpler construction.

2. Engineering Application Example

2.1. Project Overview. A commercial and residential building, which was built during 2006, is a six-story concrete frame structure. The first layer of the original design is a small and medium-sized shop with a height of 4.2 m. The second to sixth floors are residential, and the floor height is 3.0 m. In 2016, a large supermarket rented the first and second floors of this commercial and residential building. On the first floor, all the inner walls of the small shops of original design were demolished to be renovated as the main store of the supermarket, and the second floor changed the residential function division of the original design into a

Figure 1: Picture of strengthening "angle steel and batten plate."

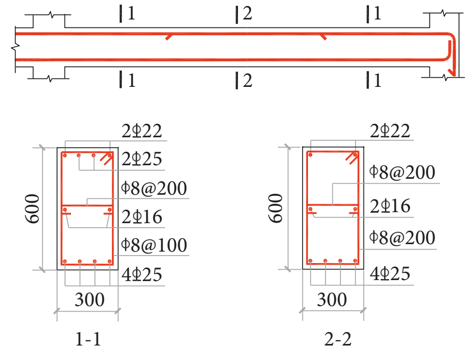

Figure 2: Diagram of reinforcement configuration of the frame beam section.

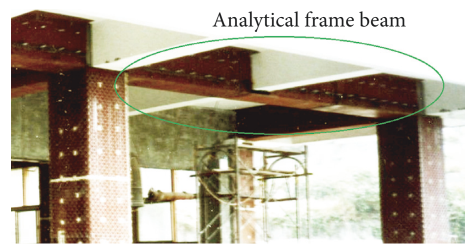

Figure 3: Picture of the RC frame beam strengthened by using the exterior-wrapping U-shaped steel plate.

supermarket warehouse. Identification is made by entrusting an appraisal unit due to changes in the using function. After reviewing the project completion data and investigating the project status and on-site nondestructive detection, it can be shown that material properties such as the concrete strength, concrete aging degree, and steel material of the bearing members such as frame beams and frame columns are in line with the current national codes and standards. Due to the change in the using function of the second layer, the checking of the bearing capacity of frame beams and frame columns of the first layer has become the key content of the identification. According to the *load code for the design of building structures* [10] (GB 50009-2012), the standard value of live load of residential buildings is 2.0 kN/m^2, and the live load of supermarket warehouses is selected according to the storage room which has a standard value of 5.0 kN/m^2. The span of the frame beam of the first layer is $l = 7200$ mm, the section size is $b = 300$ mm, and $h = 600$ mm; the configuration of reinforcement in the section is shown in Figure 2, and the section size of the frame column is 500 mm × 500 mm. It is calculated that the bearing capacity of the frame beam and frame column in the first floor is far below the requirements, so after the first floor was reinforced, the second floor can be used as a warehouse. In order to meet the requirements of Party A to ensure the net space of the main store of supermarket of the first floor, and try not to change the section size of the frame beam, finally the reinforcement scheme of strengthening RC frame beam by using the exterior-wrapping U-shaped steel plate and strengthening RC frame column by using the all-inclusive wrapping steel plate is adopted, with the thickness of the steel plate 6 mm. The images of the strengthening by using the exterior-wrapping steel plate are shown in Figure 3. Since the strengthening of concrete frame column is relatively simple, this paper only focuses on the introduction and analysis of the strengthening of the concrete frame beam.

In order to compare with the reinforcement effect of the traditional "angle steel + batten plate," the angle steel and the batten plate with the same amount of steel are reinforced with the U-shaped steel plate. The angle steel is 4L125 × 80 × 8, and the batten plate is −75 × 6@150. And the weight of the steel required for the beam is 72.6 kg/m and 72.1 kg/m. The calculation of bearing capacity and finite element analysis are carried out for the two strengthening methods.

2.2. Constructional Technology of the RC Frame Beam Strengthened by Using the U-Shaped Steel Plate. The schematic diagram of the constructional method of the RC frame beam strengthened by using the exterior-wrapping U-shaped steel plate in the engineering example is shown in Figure 4.

(1) After knocking off the plaster layer of the frame beam, polish and clean the cover

(2) Fill with epoxy resin mortar

(3) Use chemical anchors to fix and install steel plates, and ensure that the gap between steel plate and concrete is less than 3 mm; the steel plate needs to be treated with antirust (twice)

(4) Fill the gap between the steel plate and the concrete with epoxy resin and ensure it is fully filled

(5) After the outer surface of the steel plate is welded with a wire mesh (the mesh size should be smaller than 5 cm × 5 cm), restore it with a 1 : 3 cement mortar for levelling and sleeking and spray paint on it for recovery (this process is carried out according to Party A's requirements)

It can be seen from the above strengthening method that the constructional technology of strengthening RC frame beam by using the exterior-wrapping U-shaped steel plate is relatively simple. Compared with the "angle steel + batten plate" strengthening method, the most prominent advantage is time saving. The U-shaped steel plate is prefabricated in the steel structure prefabrication factory before reinforcement, which can greatly reduce the welding workload

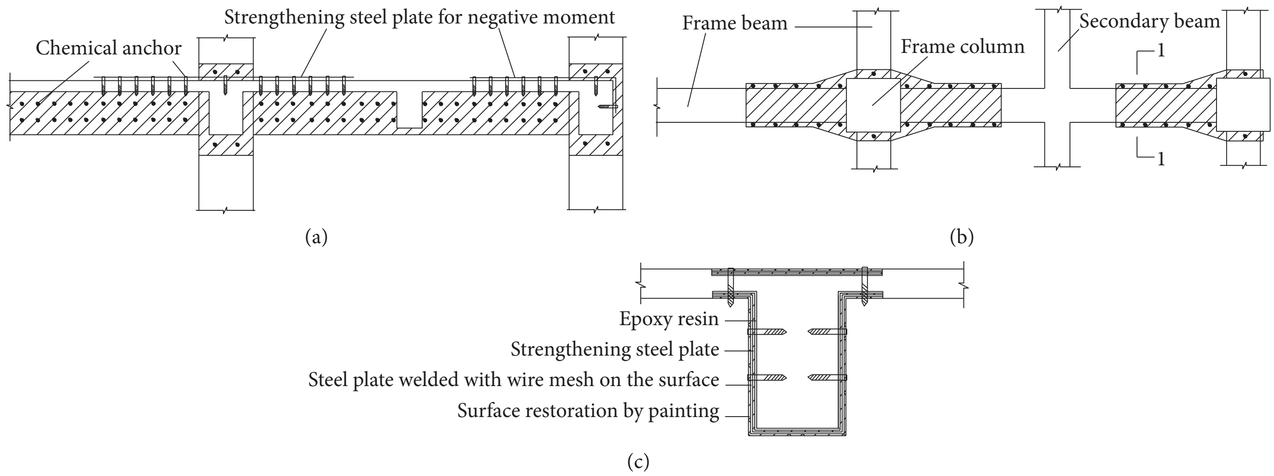

Figure 4: Schematic diagram of the strengthening constructional method: (a) reinforcement elevation; (b) reinforcement plane; (c) reinforcement profile (1-1 section).

on the construction site and achieve the purpose of shortening the construction period. However, there is a large amount of welding work in the construction site of "angle steel + batten plate" strengthening method, and the quality of the welding is difficult to guarantee, which has a lot to do with the welder's skill level. The two strengthening methods are compared further, from which the conclusion is drawn that the degree of improvement of the bearing capacity of the frame beam strengthened by using the U-shaped steel plate strengthening method is slightly greater than that by the "angle steel + batten plate" strengthening method when using the same weight of steel. The U-shaped steel plate strengthening method also has disadvantages, mainly due to the relatively large amount of epoxy resin and chemical anchor bolt, which increases the cost of reinforcement. After comprehensive consideration of material cost, labor cost, construction period, steel weight, and other factors, the most significant feature of U-shaped steel plate strengthening method is the short construction period, while the two strengthening methods are not much different in other aspects.

3. Calculation of Bearing Capacity

3.1. Calculation of Bearing Capacity of Strengthening "Angle Steel + Batten Plate". The calculation of the bearing capacity of the "angle steel + batten plate" can be directly carried out by the formula specified in the *code for design of strengthening concrete structure.*

(1) Calculation formula for flexural capacity:

$$M_u = \alpha_1 f_{c0} b x\left(h - \frac{x}{2}\right) + f'_{y0} A'_{s0}(h - a') + f'_{sp} A'_{sp} h - f_{y0} A_{s0}(h - h_0), \quad (1)$$

$$\alpha_1 f_{c0} b x = \psi_{sp} f_{sp} A_{sp} + f_{y0} A_{s0} - f'_{y0} A'_{s0} - f'_{sp} A'_{sp}, \quad (2)$$

$$\psi_{sp} = \frac{(0.8\varepsilon_{cu} h/x) - \varepsilon_{cu} - \varepsilon_{sp,0}}{f_{sp}/E_{sp}}, \quad (3)$$

where M_u represents the flexural capacity of reinforced members, α_1 is the ratio of the stress value of the rectangular stress diagram of concrete in the compression zone to the design value of concrete axial compressive strength; f_{c0} is the design value of compressive strength of concrete axis of the original member; x represents the height of the concrete compression zone, and $x \geq 2a'$; a' is the distance from the resultant point of longitudinal compression reinforcement to the near side of section; h_0 represents the effective height of the section before reinforcement; b and h are the width and height of the rectangular section, respectively; f_{y0} and f'_{y0} are the design values of tensile and compressive strengths of steel reinforcement in the original member, respectively; f_{sp} and f'_{sp} are the design values of tensile and compressive strengths of reinforced U-shaped steel, respectively; A_{sp} and A'_{sp} are the section area of the tension angle and compression angle, respectively; A_{s0} and A'_{s0} are the section area of tensile and compressive reinforcements in the original member, respectively; ψ_{sp} represents the reduction factor considering that the tensile strength of tensile angle steel may not reach the design value when taking the influence of secondary forces into account, and ψ_{sp} = 1.0 when $\psi_{sp} > 1.0$; ε_{cu} is the ultimate compressive strain of concrete, taking $\varepsilon_{cu} = 0.0033$; and $\varepsilon_{sp,0}$ is the hysteresis strain of tension angle steel when considering the influence of secondary forces, taking $\varepsilon_{sp,0} = a_{sp} M_{0k}/E_s A_s h_0$, and $\varepsilon_{sp,0} = 0$ if not considering the influence of secondary force. a_{sp} represents the calculated coefficients overall considering the variation of the moment arm in the crack section, the inhomogeneity of the tensile strain of the reinforcement and the arrangement of the reinforcement of the bending member according to the *code for design of strengthening concrete structure* (GB50367-2013); M_{0k} is the standard value of bending moment acting on the checking section of flexural member before reinforcement.

(2) Calculation formula for shear capacity

$$V_u = V_{b0} + V_{b,sp}, \tag{4}$$

$$V_{b0} = \alpha_{cv} f_t b h_0 + f_{yv} \frac{A_{sv}}{s} h_0, \tag{5}$$

$$V_{b,ps} = \frac{\psi_{vb} f_{sp} A_{b,sp} h_{sp}}{s_{sp}}, \tag{6}$$

where V_u represents the shear capacity of the strengthened member; V_{b0} is the shear capacity of the beam before reinforcement; $V_{b,sp}$ represents the incremental shear capacity of the beam after reinforcement; α_{cv} is the shear capacity coefficient of concrete with inclined section of the original member, taking 0.7 for general flexural members; f_t is the design value of axial tensile strength of concrete of the original member; f_{yv} represents the design value of the tensile strength of stirrup of the original member; A_{sv} is the total cross-sectional area of each stirrup configured in the same section of the original member, i.e., nA_{sv1}, where n is the number of stirrup legs in the same section and A_{sv1} is the cross-sectional area of single limb stirrup; s represents the stirrup spacing along the length of the original member; ψ_{vb} is the shear strength reduction factor related to the bonding mode and stress condition of the hoop plate, according to the *code for design of strengthening concrete structure* (GB50367-2013), as shown in Table 1; $A_{b,sp}$ is the total cross-sectional area of each hoop plate configured in the same section, i.e., $2b_{sp}t_{sp}$, where b_{sp} (Figure 5) and t_{sp} are the width and thickness of the hoop plate, respectively; h_{sp} represents the vertical height of the hoop plate pasted on the side of the beam; and s_{sp} represents the hoop plate spacing along the length of the member.

3.2. Calculation of Bearing Capacity of Strengthening by Using the U-Shaped Steel Plate. Although the strengthening by using the U-shaped steel plate strengthening method is different from the "angle steel + batten plate" strengthening method specified in the *code for design of strengthening concrete structure*, it can still refer to the *code for design of strengthening concrete structure* and *code for design of concrete structures* (GB50010-2010) [11]. The calculation formula for the bearing capacity of the RC frame beam strengthened by using the exterior-wrapping U-shaped steel plate is briefly derived.

3.2.1. Calculation Formula for Flexural Capacity. In addition to the assumptions in the specification, the following assumptions are made: the chemical anchor can not only fix the U-shaped steel plate on the outer surface of the beam but also prevent local buckling of the steel plate if spacing is set properly. When the high-thickness ratio of web meets the requirements of "plastic design" in *standard for design of steel structures* (GB50017-2017) [12], the plastic design method can be used for simplified calculation. The RC frame beam strengthened by using the exterior-wrapping U-shaped steel plate belongs to the category of the steel-concrete composite beam, and the simplified calculation by using the plastic design method also conforms to the provisions of *code for design of composite structures* (JGJ138-2016) [13] and *code for design of steel and concrete composite bridges* (GB50917-2013) [14].

Assume that the portions of the U-shaped plate located on either side of plastic neutral axis bear uniform stress and achieve the steel tensile or compressive strength design value, and the plane cross-section assumption is always true during deformation. Fix the steel plate with a chemical anchor bolt, and pour epoxy resin into the crack between steel plate and concrete to prevent the slipping on the interface between steel plate and concrete. Ignoring the beneficial effect of reinforced concrete flange slabs on frame beams, the internal force relationship of the RC frame beam section is shown in Figure 6. According to Figure 6, it can be deduced as follows.

$$\left.\begin{aligned} N_c &= xbf_{c0}, \\ N_s' &= A_{s0}' f_{y0}', \\ N_s &= A_{s0} f_{y0}, \\ N_{sp1} &= 2xt f_{sp}', \\ N_{sp2} &= 2\psi_{sp}(h-x)t f_{sp}, \\ N_{sp3} &= \psi_{sp} bt f_{sp}, \end{aligned}\right\} \tag{7}$$

$$\left.\begin{aligned} M_c &= N_c (x/2), \\ M_s' &= N_s'(x-a'), \\ M_s &= N_s (h-x-a), \\ M_{sp1} &= N_{sp1}(x/2), \\ M_{sp2} &= N_{sp2}(h-x)/2, \\ M_{sp3} &= N_{sp3}(h-x-t/2). \end{aligned}\right\} \tag{8}$$

Due to $\sum N = 0$,

$$N_c + N_s' + N_{sp1} = N_s + N_{sp2} + N_{sp3}. \tag{9}$$

Due to $\sum M = 0$, the ultimate bending capacity is obtained

$$M_u = M_c + M_s' + M_s + M_{sp1} + M_{sp2} + M_{sp3}, \tag{10}$$

where N_c is the resultant force of concrete in the compression zone, N_s' is the resultant force of the steel in the compression zone, N_s is the resultant force of the steel in the tensile zone, N_{sp1} is the resultant force of the webs on both sides of the compression zone, N_{sp2} is the resultant force of the webs on both sides of the tensile zone, and N_{sp3} is the resultant force of base plate of the bottom flanges. And resistance moment of concrete in the compression zone is denoted as M_c, resistance moment of the steel in the compression zone as M_s', resistance moment of the steel in the tensile zone as M_s, the resistance moment of the webs on

Table 1: Value of the shear strength reduction factor ψ_{vb}.

Make up of the hoop plate		Adding anchor seal hoop	Rubber anchor or steel anchor U-hoop	General U-shaped hoop
Stress condition	Uniform load or shear span ratio $\lambda \geq 3$	1.00	0.92	0.85
	Shear span ratio $\lambda \leq 1.3$	0.68	0.63	0.58

When λ is the median, the value of ψ_{vb} is determined by linear interpolation.

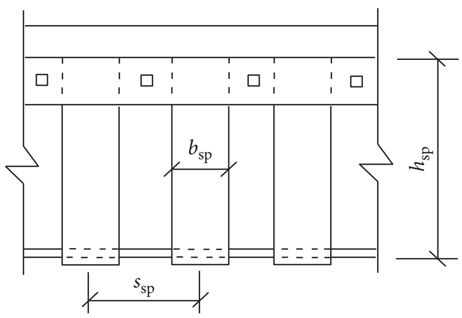

Figure 5: Schematic diagram of the hoop plate layout.

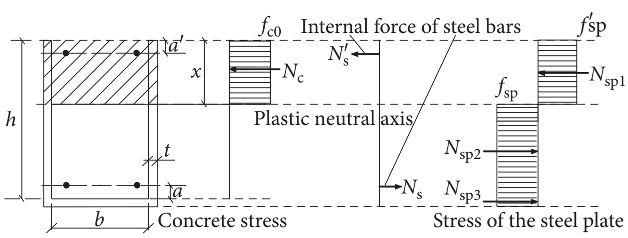

Figure 6: Calculation chart of ultimate moment.

both sides of the compression zone as M_{sp1}, the resistance moment of the webs on both sides of the tensile zone as M_{sp2}, and the resistance moment of base plate of the bottom flanges as M_{sp3}; a represents the distance from the resultant point of longitudinal tensile reinforcement to the near side of the section.

3.2.2. Calculation Formula for Shear Capacity. The shear resistance of the reinforced concrete flange slab is relatively large, and it is a safety consideration to ignore its beneficial effect on the RC beam. According to the provisions of *code for design of composite structures* JGJ138-2016 and *code for design of steel and concrete composite bridges* GB50917-2013, the contribution of the U-shaped steel plates to the shear capacity of concrete beams is

$$V_{sp} = 2 f_{spv} t h, \tag{11}$$

where f_{spv} represents the design value of the shear strength of the steel plate, $f_{spv} \approx 0.58 f_{sp}$ according to the *standard for design of steel structures* GB50017-2017, and t is the thickness of the U-shaped steel plate.

It is not difficult to find from formula (6) that, when $s_{sp} = b_{sp}$ (Figure 5), each limb of the hoop plates will be connected into a whole, which can be seen equivalently as the web of the U-shaped steel. It can be deduced as follows:

$$\begin{aligned} V_{b,ps} &= \frac{\psi_{vb} f_{sp} A_{b,sp} h_{sp}}{s_{sp}} \\ &= \frac{2\psi_{vb} f_{sp} b_{b,sp} t_{b,sp} h_{sp}}{s_{sp}} \\ &= 2\psi_{vb} f_{sp} t_{sp} h_{sp}. \end{aligned} \tag{12}$$

Comparing formulas (11) and (12) and still selecting ψ_{vb} from Table 1, it can be seen that the contribution of the U-shaped steel plate reinforcement and "angle steel + batten plate" reinforcement to the shear capacity of the beam is consistent, while formula (12) considers it in more detail. Therefore, the shear capacity of the strengthening beam by using the U-shaped steel plate is

$$V_u = V_{b0} + V_{sp} = \alpha_{cv} f_t b h_0 + f_{yv} \frac{A_{sv}}{s} h_0 + 2\psi_{vb} f_{sp} t h. \tag{13}$$

Note: The symbols appearing in formulas (1)–(13) have the consistent meaning, and they have been defined only in the first instance.

4. Finite Element Analysis

Using the finite element analysis software ABAQUS, the finite element modelling of the frame beam of the engineering example is carried out before and after reinforcement, and comparative analysis is carried out.

4.1. Constitutive Relationship of Materials. The constitutive relationship of concrete is based on the concrete damaged plasticity model [15–17]. It is assumed that the concrete failure mode is compression crushing or tensile cracking. The compression and tension of constitutive relations are shown in Figure 7. According to the *code for design of concrete structures* and literature [18], the elastic modulus of C30 concrete is $E_c = 3.0 \times 10^4$ MPa and Poisson's ratio is $\nu_c = 0.2$, with expansion angle 30°, eccentricity ratio 0.1, $f_{b0}/f_{c0} = 1.16$, $k_c = 0.667$, and viscosity coefficient 0.0003. When the computation does not converge, the viscosity coefficient needs to be adjusted.

Both the constitutive relationship of the steel bar and the constitutive relationship of the steel plate are bilinear models [19–21], and the constitutive relations between compression and tension are shown in Figure 8. According to the *code for design of concrete structures* and *standard for design of steel structures*, stressed steel bar adopts HRB335: E_s (elastic modulus) $= 2.0 \times 10^5$ MPa. The stirrup adopts HPB235: $E_s = 2.1 \times 10^5$ MPa. And the steel plate and steel

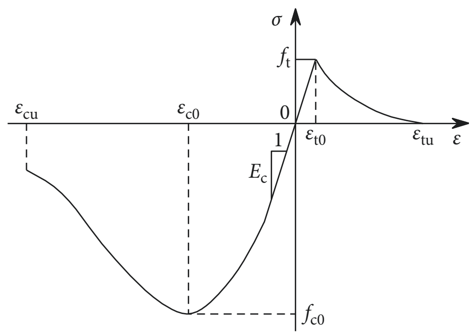

Figure 7: Constitutive relationship of concrete.

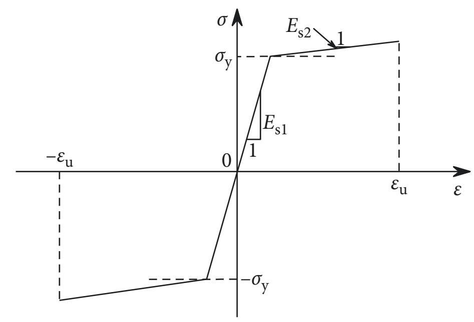

Figure 8: Constitutive relationship of steel.

angle both adopt Q235: $E_s = 2.06 \times 10^5$ MPa. ν_s (Poisson's ratio of all) = 0.3.

4.2. Finite Element Model. When ABAQUS is used for analysis, a separated modelling method is adopted. While the steel plate, angle steel, batten plate, concrete, and beam bearing are all modelled by using the three-dimensional solid element C3D8R, the longitudinal reinforcements and stirrups are all modelled by using the three-dimensional bar member T3D2 [22, 23], with the mesh size of 0.05, regardless of the relative slip between steel bars and concrete. Use the embedded command in ABAQUS software to embed the steel bars in the concrete, fix the steel plate with chemical anchors, and the epoxy resin is poured between the concrete and the steel plate to guarantee the coordinated deformation of the two. And the concrete is combined with the reinforcing steel plate by using the tie command, taking the steel plate as the main surface, which ensures that the steel and concrete are fully engaged and the displacement is coordinated; angle steel, hoop plate, and concrete are also bound by the tie command [24–26]. The boundary condition of the beam end bearing is simulated by using a fixed connection, i.e., all 6 degrees of freedom are 0. The finite element models of the reinforced skeleton frame, plain concrete, U-shaped strengthening steel plate, frame beam strengthened with the U-shaped steel plate, and frame beam strengthened with the "angle steel + batten plate" for contrast are all shown in Figure 9. In order to avoid the local damage caused by the concentrated load, a rectangular discrete steel sheet and a reference point are set up in the beam loading point for applying the concentrated load; the monotonic static loading method of displacement control is used to load; the general algorithm is selected for calculation, and automatic increment is selected for control.

4.3. Finite Element Calculation Results and Analysis

4.3.1. Relationship of Load and Deflection. The load and midspan deflection curves of finite element analysis before and after reinforcement of RC frame beams are shown in Figure 10. It can be seen from Figure 10 that the flexural capacity of RC frame beams is obviously improved after reinforcement, and frame beams strengthened by the U-shaped steel plate are improved by 78%, and the frame beams for contrast strengthened by "angle steel + batten plate" increase by 69% The deflection corresponding to ultimate bearing capacity after reinforcement is also slightly reduced, which is 16 mm before reinforcement and is 13 mm after reinforcement. The frame beam after reinforcement also shows a certain degree of ductility, and the rate of decline of the bearing capacity is slower than that before the reinforcement. The deflections before and after the reinforcement are 22 mm, 24 mm, and 23 mm, respectively. It shows that the bending stiffness after reinforcement is also obviously improved and the ultimate damage after ultimate load shows a certain degree of ductility. Comparing the two strengthening methods, the U-shaped steel plate strengthening method can maintain RC frame beams with high bearing capacity and good ductility. Strengthened with "angle steel + batten plate," the bending stiffness deteriorates rapidly after the frame beam reaches the ultimate bearing capacity.

4.3.2. Stress Field of Frame Beam Strengthened by Using the U-Shaped Steel Plate. The stress field corresponding to the peak value of the U-shaped steel plate reinforcement curve in Figure 10 is shown in Figure 11. After calling post-processing data and combined with Figure 9, it can be seen that the tensile stresses of the reinforcement bar of the steel skeleton in the midspan and the support both reach the yield strength, with the compressive reinforcement stress reaching 88% of the yield strength; the stress at the loading point in the upper compression zone in the midspan of concrete reaches the designed value of concrete axial compressive strength f_{c0}, and the edge stress of the compression zone in the lower part of the support reaches 92% of the designed value of concrete axial compressive strength f_{c0}; the stresses at the edge of the tension zone in the lower part of the midspan and the upper part of the support reach the designed value of the designed value of the concrete axial tensile strength f_t, which means the concrete has been pulled apart; the upper and lower edge stresses in the midspan and support all reach the yield strength, which indicates that the thickness of the U-shaped steel plate is suitable.

4.3.3. Comparison of Finite Element Calculation and Theoretical Formula Calculation. When the lateral displacement

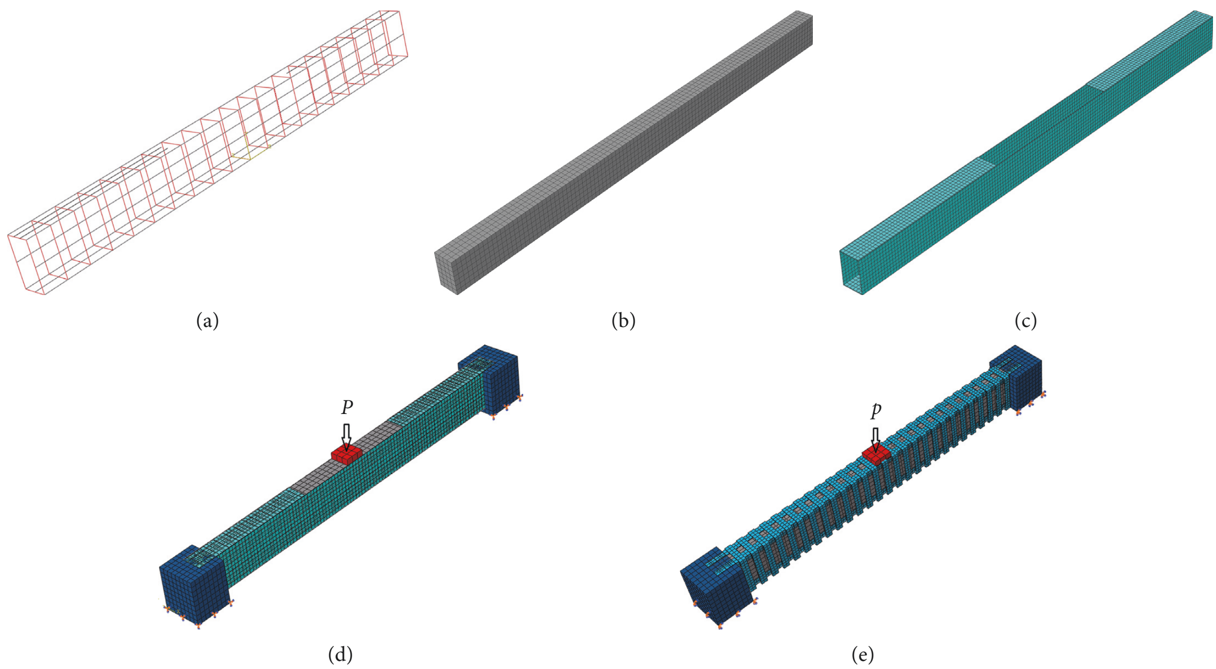

FIGURE 9: Finite element model of (a) reinforcement skeleton, (b) concrete, (c) steel plate for strengthening, (d) reinforced frame beam, and (e) reinforced RC beam for contrast.

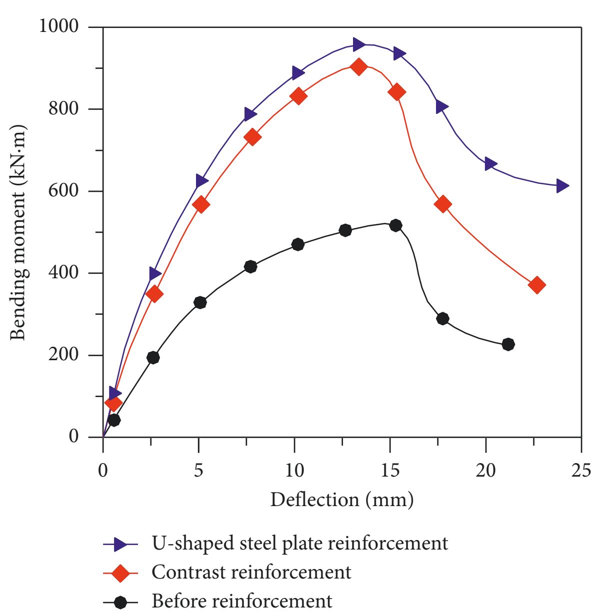

FIGURE 10: Bending moment-deflection relation.

of the frame is not considered, the iteration method is used to calculate the moment design value M of the frame beam after the second layer of the frame structure changed to the supermarket warehouse, and then the free body is taken to calculate the shear force design value V of the bearing. According to the *code for design of concrete structures*, the ultimate flexural capacity and ultimate shear capacity of the frame beam before reinforcement are calculated. According to formulas (10) and (13) and combined with the *code for design of strengthening concrete structure*, the ultimate flexural capacity and ultimate shear capacity of the frame beam after the reinforcement by using the U-shaped steel plate are calculated, respectively. Then using the formulas (1) and (4), the ultimate flexural capacity and ultimate shear capacity of the frame beam strengthened by using the "angle steel + batten plate" are calculated, respectively. And then the above calculation results are compared with the finite element calculation results, as shown in Table 2.

It can be seen from Table 2 that the flexural capacity and shear capacity before reinforcement are less than the design value, and the bearing capacity does not meet the requirements. The finite element calculation results and the theoretical formula calculation results after reinforcement are larger than the design value and meet the bearing capacity requirements. At the same time, it can be seen that the ratio of the finite element calculation result to the theoretical formula calculation result is in the range of 0.91~0.96 before and after reinforcement. The calculation results of the flexural capacity and shear capacity before reinforcement and the shear capacity after reinforcement obtained by these two methods are with less error and more consistence, which proves that ABAQUS analysis meets the requirements of engineering design and engineering appraisal and strengthening. The ratio of the calculated results of the flexural capacity after reinforcement obtained by the two methods is 0.91, and the error is relatively large. The reason is probably that when deriving the theoretical calculation formula, the theoretical calculation results are too large due to the assumption that the steel plates on both sides are designed according to the full-section plasticity. Therefore, it is more reasonable for the calculation formula of the flexural capacity after reinforcement to calculate according to the elastoplastic design, and the plastic development coefficient

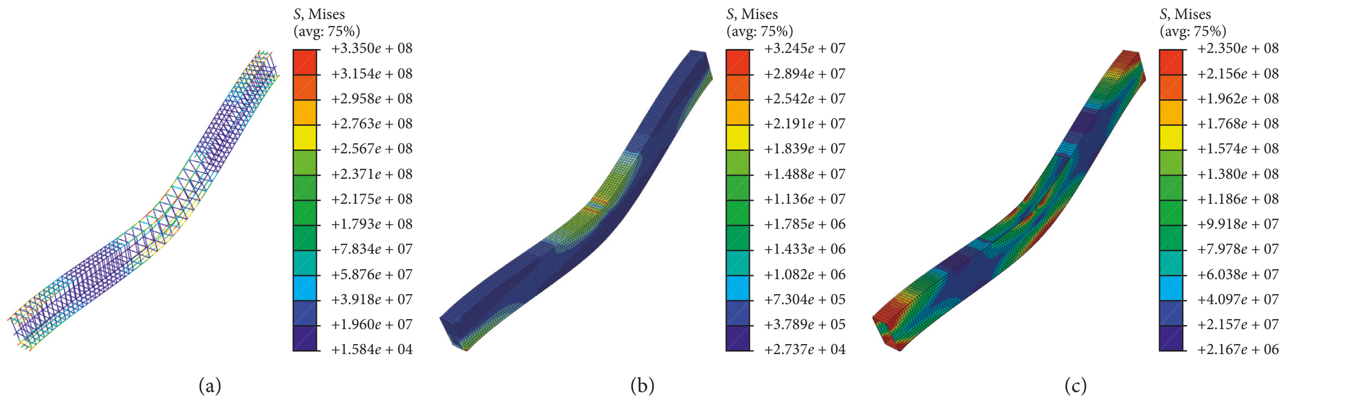

Figure 11: Peak stress field of the U-shaped steel plate reinforcement curve. Stress field of (a) reinforcement skeleton, (b) concrete, and (c) U-shaped steel plate.

Table 2: Review and comparison of bearing capacity.

Bearing capacity	Design value	Before reinforcement			U-shaped steel plate reinforcement			Contrast reinforcement		
		Finite element calculation	Theoretical calculation	Ratio	Finite element calculation	Theoretical calculation	Ratio	Finite element calculation	Theoretical calculation	Ratio
M (kN·m)	776	535	567	0.94	954	1047	0.91	904	938	0.96
V (kN)	471	289	302	0.96	680	715	0.95	530	555	0.95

The ratio is the ratio of the finite element calculation result to the theoretical calculation result.

should be supplemented with the necessary structural tests for further confirmation. In addition, from Table 2, it can be calculated that the ratio of the ultimate flexural capacity and the ultimate shear capacity obtained by the two strengthening methods are 1.07 and 1.28, respectively, indicating that with the same amount of steel in strengthening, the increased bearing capacity of the U-shaped steel plate strengthening method is slightly greater than that of the "angle steel + batten plate" strengthening method.

5. Conclusions

The strengthening method by using the exterior-wrapping U-shaped steel plate is suitable for the reinforcement of concrete members that need to greatly improve the bearing capacity without increasing the section size, with the characteristics of small influence on the section size and aesthetics, simple construction, and operation and fast construction speed. Compared with the "angle steel + batten plate" reinforcement method, it has better comprehensive performance.

The bearing capacity of the RC frame beam strengthened by using the exterior-wrapping U-shaped steel plate can be calculated by referring to the formula that is simply derived from the *code for design of strengthening concrete structure*, and the calculation result meets the engineering requirements.

In the case of RC frame beams strengthened by using the exterior-wrapping U-shaped steel plate, in addition to using the theoretical formula to calculate the bearing capacity, it is recommended to use ABAQUS, ANSYS, and other software for modelling to carry out finite element analysis and comparison calculation, and if necessary, additional structural tests are needed for further verification.

It has been nearly two years since the project was put into use after reinforcement. According to feedbacks from Party A and later observations, no abnormal phenomena were found, which indicates that the reinforcement of RC beams strengthened by using the U-shaped steel plate achieves the expected goal.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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