Research Article

Analysis of the Bearing Capacity of a Steel Structural Member after Reinforcement

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To improve the bearing capacity of existing angle steel structures, a new and cost-effective reinforcement method for increasing the load-bearing capacity is proposed. This method uses steel pipes as auxiliary materials and clamps the reinforced angle steel and the auxiliary materials through fixtures to ensure that they are deformed together. The influence of the fixture spacing, the size of the reinforced angle steel member, the slenderness ratio of the members, the size of the auxiliary steel pipe, and other parameters on the reinforcement effect is studied. The results show that the smaller the fixture spacing is, the more obvious the improvement of the bearing capacity is, and the reasonable fixture spacing is related to the angle steel leg width. The larger the slenderness ratio of the member is, the more obvious the reinforcement effect of the scheme is. The steel pipe size has a significant impact on the reinforcement effect of the scheme.

1. Introduction

Due to the large slenderness ratio and special section form, hot-rolled steel members of steel structures have serious tension and compression asymmetry. When these members are subjected to bending moments and pressures, instability and damage often occur, and the material strength cannot be fully utilized. The failure of angle steel structure is mostly point instability failure. When the weak members of a steel structure are unstable, the bearing capacity decreases rapidly, causing a chain reaction in local areas, which leads to the overall collapse of the structure. In recent years, with the continuous increase in load, the bearing performance of some steel structures cannot meet the existing design requirements [1, 2].

At present, scholars worldwide have studied reinforcement schemes for steel structures with different types and service states. The reinforcement of angle steel structures can be divided into two categories: adding transverse support members and strengthening the restraint on the buckling behavior of weak members [3, 4]. The overall bearing capacity of a steel structure can be effectively improved by adding transverse support [5, 6]. Albermani et al. [7] added transverse supports to the weak parts of a transmission tower to improve the bearing capacity of the tower. By carrying out experiments, Albermani et al. [7] studied the influence of parameters such as different forms of transverse supports and locations of transverse supports on the bearing capacity of the steel structure. Yang et al. [8] established a numerical model for a steel structure and studied the effect of transverse partitioning on the wind resistance calculation of the tower. This researcher concluded that a reasonable setting of the transverse partition can prevent the premature appearance of local formation and reduce the internal force of the main material. However, the calculation scheme of the bearing capacity is not clear after adding transverse support, and the additional support needs to be effectively connected to the original structure through special design, so there are difficulties in design and construction. Strengthening the restraint on the buckling behavior can reinforce weak members, and this kind of reinforcement has various forms, and reasonable reinforcement forms can be selected according to different types of transmission towers and design requirements [9, 10]. Scholars worldwide have carried out a series of studies on the
buckling behavior of restrained angle steel. Adding auxiliary materials is an economical and effective way to provide restraint to angle steel. Mills et al. [11] used the form of parallel auxiliary materials to constrain the buckling behavior of angle steel. Lu and coworkers [12] reinforced the original angle steel by drilling holes in the main material and connecting plates to connect auxiliary materials. These investigators carried out substructure tests to study the influence of bolt cross connectors on the bearing performance of transmission towers. Welding and bolted connections are common connections between auxiliary materials and angle steel. The welding residual stress and bolted connection can damage the original angle steel [13–16]. A kind of strengthening scheme, which is convenient for construction and has little influence on the original structure, is to connect auxiliary material to the original angle steel effectively through a fixture [17, 18].

Commonly used auxiliary materials include angle steel, steel plates, channel steel, and other open section steel members with poor buckling capacity. Fixtures with complex forms have reduced practicability and reinforcement convenience. In this paper, a new scheme for improving the bearing capacity of angle steel is proposed, which uses a steel pipe as an auxiliary material to reinforce the original angle steel. The bearing capacity of the steel pipe is much higher than that of the steel member with the same specification because of its symmetrical cross section and isotropic mechanical properties. The use of fixtures to connect auxiliary materials and angle steel reduces the secondary damage to angle steel components.

2. Model Establishment

2.1. Finite Element Modeling. In the new antibuckling capacity improvement scheme, a steel pipe is adopted as an auxiliary material; this pipe is fixed to the inner side of the angle steel by using fixtures and bolts, as shown in Figure 1. By tightening the bolts, a pretightening force is applied to the steel tube and the angle steel to strengthen the cooperative work between them.

The finite element model of the component was established in ABAQUS to study the buckling shape and bearing capacity of the component before and after reinforcement. The component is modeled by a solid element, which is divided into 8-node hexahedral solid elements (C3D8R). Figure 2 is a schematic diagram of mesh division. The mesh size is determined according to the force complexity of different components. Bolts, fixtures, and angle steel parts with complex forces are divided into small meshes, and the mesh size is controlled at 1/500 of the maximum length of the parts. The steel pipe mesh size is controlled at 1/100 of the maximum length of the part. The end plate mesh size is controlled at 1/10 of the maximum length of the part. Both ends of the angle steel are fixed to the end plate, and both ends of the steel pipe are 250 mm away from the end plate. To ensure that the axial displacement is applied to the members, one end of the member is completely fixed, and only the axial displacement is released at the other end.

2.2. Component Selection. To study the influence of different parameters on the reinforcement effect of angle steel, numerical models of various components were established, and parametric research of a new reinforcement scheme was carried out. Specifications of various components are shown in Table 1. A total of 27 components were selected for parameter analysis.

Fixtures and bolts need to be strong enough to ensure that their failure occurs after the bar buckles and produces a large deformation. The thickness of the steel plate used in the fixture is uniformly determined to be 6.0 mm, and the width of the fixture is uniformly 80.0 mm. The section size of the fixture varies proportionally with the size change in the angle steel. Figure 4 is a schematic diagram of fixture installation. In component number such as L100 × 10G57SR75-1150, L100 × 10 represents limb width of angle steel which is 100 mm, limb thickness is 10 mm, G57 represents the steel pipe diameter which is 57 mm, SR75 represents angle steel member slenderness ratio which is 75, and –1150 represents fixture spacing which is 1150 mm.
Figure 3: Bilinear constitutive model of steel.

Table 1: Component specification sheet.

| Member number | Section size of angle steel (mm) | Section size of steel tube (mm) | Slenderness ratio of angle steel | Length of angle steel (mm) | Fixture spacing (mm) | The ratio of the fixture spacing to angle steel limb width |
|---------------|---------------------------------|---------------------------------|---------------------------------|---------------------------|-------------------|------------------------------------------------------|
| L63 × 5G0SR75-0 | 63 5 1 20 | 75 1875 | 75 1875 | 1150 11.5 |
| L100 × 10G0SR75-0 | 100 10 1 20 | 75 3000 | 75 3000 | 1150 11.5 |
| L140 × 14G0SR75-0 | 140 14 1 20 | 75 4125 | 75 4125 | 1150 11.5 |
| L63 × 5G34SR75-587 | 63 5 34 2.0 75 1875 | 75 1875 | 75 1875 | 1150 11.5 |
| L63 × 5G34SR75-392 | 63 5 34 2.0 75 1875 | 75 1875 | 75 1875 | 1150 11.5 |
| L100 × 10G57SR75-630 | 100 10 57 4.0 75 3000 | 75 3000 | 75 3000 | 1150 11.5 |
| L100 × 10G57SR75-765 | 100 10 57 4.0 75 3000 | 75 3000 | 75 3000 | 1150 11.5 |
| L100 × 10G57SR75-850 | 100 10 57 4.0 75 3000 | 75 3000 | 75 3000 | 1150 11.5 |
| L100 × 10G57SR75-950 | 100 10 57 4.0 75 3000 | 75 3000 | 75 3000 | 1150 11.5 |
| L140 × 14G76SR75-1712 | 140 14 76 5.5 75 4125 | 75 4125 | 75 4125 | 1150 11.5 |
| L140 × 14G76SR75-1142 | 140 14 76 5.5 75 4125 | 75 4125 | 75 4125 | 1150 11.5 |
| L140 × 14G76SR75-855 | 140 14 76 5.5 75 4125 | 75 4125 | 75 4125 | 1150 11.5 |
| L140 × 14G76SR75-685 | 140 14 76 5.5 75 4125 | 75 4125 | 75 4125 | 1150 11.5 |
| L140 × 14G76SR75-570 | 140 14 76 5.5 75 4125 | 75 4125 | 75 4125 | 1150 11.5 |
| L140 × 14G76SR75-490 | 140 14 76 5.5 75 4125 | 75 4125 | 75 4125 | 1150 11.5 |
| L100 × 10G57SR55-575 | 100 10 57 4.0 55 2180 | 75 2180 | 75 2180 | 1150 11.5 |
| L100 × 10G57SR95-575 | 100 10 57 4.0 95 3700 | 75 3700 | 75 3700 | 1150 11.5 |
| L100 × 10G57SR115-575 | 100 10 57 4.0 115 4500 | 75 4500 | 75 4500 | 1150 11.5 |
| L100 × 10G40SR75-575 | 100 10 40 2.5 75 3000 | 75 3000 | 75 3000 | 1150 11.5 |
3. Parameter Analysis of the New Reinforcement Scheme

The effect of a new reinforcement scheme on the bearing capacity of an angle steel member is complicated, as it is influenced by the fixture spacing, component slenderness ratio, size of the steel pipe and the angle steel component, fixture width, and bolt arrangement on the fixture. In this paper, four parameters, including the fixture spacing, size of the angle steel member, slenderness ratio, and size of the steel pipe, were selected for analysis, and the influence rule of parameter change on the bearing performance of the original angle steel member was studied. The improvement rate of the bearing capacity after reinforcement is defined as $\alpha$.

$$\alpha = \frac{c_1 - c_2}{c_2} \times 100\%,$$

where $\alpha$ is the improvement rate of the bearing capacity after reinforcement, $c_1$ is the bearing capacity of the component after reinforcement, and $c_2$ is the bearing capacity of the original angle steel.

3.1. Fixture Spacing. In this paper, angle steel components of L63 × 5 mm, L100 × 10 mm, and L140 × 14 mm were selected to study the influence of the fixture spacing. The angle steel component, steel pipe, and other hot-rolled steel members have a definite specification. To ensure a single variable, the relative size of the steel pipe and angle steel limb was fixed in the same range. The outside diameter of the steel pipe is 50–60% of the width of the angle steel limb, the wall thickness of the steel pipe is 35%–40% of the wall thickness of the angle steel limb, and the cross-sectional area of the steel pipe is 25%–35% of the angle steel member. The component specifications are shown in Table 1.

When the section size of the angle steel reinforcement is L63 × 5 mm, as shown in Figure 5, the bearing capacity of the component increases with decreasing fixture spacing. The maximum bearing capacity is exhibited on the L63 × 5G34SR75-235 member with the smallest fixture spacing, and the maximum bearing capacity is 85.4% of the tensile yield capacity of the member. The bearing capacity of reinforced components is negatively correlated with fixture spacing. When the fixture spacing is 587 mm and 392 mm, the bearing capacity of the member is increased by 7.8% and 14.8%, respectively. Compared with the angle steel member, the bearing capacity is not significantly improved. When the fixture spacing is 295 mm and 235 mm, the lifting rate of the bearing capacity is 37.7% and 41.3%, respectively. When the fixture spacing is less than 295 mm, with decreasing fixture spacing, the bearing capacity of the component does not improve significantly, indicating that there is a reasonable range of fixture spacing. When the fixture spacing is less than a reasonable range, the bearing capacity cannot be improved.
effectively. When the fixture spacing is greater than a reasonable range, the bearing capacity of the component does not improve significantly.

The buckling morphology of each component before and after reinforcement is shown in Figure 6. Initial defects should be given for the buckling analysis of angle steel components. The initial defect is uniformly set to 1‰ of the length of the angle steel. When applying initial defects, the component is regarded as a whole, and initial defects are applied to the steel pipe and angle steel. In this paper, the first-order buckling mode of the member is taken as the application form of the initial defect, and the first-order buckling mode of the member is determined by the nonlinear buckling analysis of the member. The coordinates of each element of the member in the first-order buckling mode are multiplied by the corresponding scale factor and then introduced into the static analysis. When the original angle steel member buckles, the stress concentration is obvious in the middle and both ends of the component, as shown in Figure 6 for member L63×5G34SR75-587. Large displacement and deformation occur in the middle part. Members L63×5G34SR75-587, L63×5G34SR75-392, and L63×5G34SR75-295 are similar to the original angle steel component in terms of their flexural morphology, with large deformation in the middle. The buckling shape of member L63×5G34SR75-235 is slightly different, and the buckling point of the member is moved up, but all the members suffer from overall buckling instability.

The original angle steel member is reinforced with a new reinforcement scheme, and the buckling bearing capacity of the original angle steel can be effectively improved by reasonably setting the fixture spacing. The buckling characteristic of the member, that is, the overall buckling instability, exhibits no obvious change. After reinforcement, the ductility of the angle steel member demonstrates no obvious improvement.

Figure 7 shows the force-displacement curves of the L100×10 mm angle steel before and after reinforcement. After reinforcement, the buckling bearing capacity of L100×10G57SR75-765, L100×10G57SR75-575, L100×10G57SR75-460, L100×10G57SR75-385, and L100×10G57SR75-325 increases significantly, and the lifting rate A exceeds 50.0%. When the distance between the fixtures is more than 765 mm, the increase in the buckling capacity of the components is small.

After reinforcement, the ductility of the member is significantly improved. After the bearing capacity of the member reaches the maximum value, with a continuous increase in the end displacement, the bearing capacity of the member decreases gradually. The members L100×10G57SR75-460, L100×10G57SR75-385, and L100×10G57SR75-325 exhibit the best ductility performance.

Figure 8 shows the buckling shape of each member. The members L100×10G0SR75-0 and L100×10G57SR75-1150 showed overall buckling. When the bearing capacity exceeds the buckling bearing capacity and then decreases rapidly, the ductility of the member with overall buckling is poor. L100×10G57SR75-575 first suffered from local buckling, and with a continuous increase in the displacement, the deformation of the middle part of the member increases, showing the overall buckling shape. When the member begins to buckle locally, its bearing capacity reaches the maximum value at the same time, the local buckling characteristic becomes increasingly obvious with an increase in the end displacement, and the bearing capacity of the member decreases slowly. When the end displacement continues to increase, the overall buckling of the member occurs, and the bearing capacity decreases rapidly. Component L100×10G57SR75-385 exhibits local buckling, and there is clear local deformation of the angle steel between the two fixtures near the end. After local buckling, the bearing capacity shows no obvious drop. With the increasing end displacement, the component shows good ductility.

With the reduction in the fixture spacing, the new reinforcement scheme has a more obvious effect on the bearing capacity of the angle steel member, the ductility of the components is significantly improved, and the bearing performance is improved. When the distance between the fixtures is less than 575 mm, the bearing capacity and ductility of the components are both improved. When the distance between the fixtures is greater than 575 mm, the ductility characteristics of the components are not obvious, and the effect of improving the bearing capacity is limited.

When the section size of the angle steel member increases to L140×14 mm, the bearing capacity of the components increases significantly with decreasing fixture spacing. When the fixture spacing is less than 855 mm, the buckling capacity of the components does not change significantly with decreasing fixture spacing. Therefore, when the fixture spacing is less than 855 mm, the influence of fixture spacing on the bearing capacity of the reinforced components is weakened.

The ductility of the component is improved after reinforcement. As shown in Figure 9, the members show a certain ductility after buckling. As shown in Figure 10, the
buckling characteristics of the members before and after reinforcement are referred to as global buckling. In member L140 × 14G0SR75-0, by increasing end displacement, the central deformation gradually increases, and, finally, overall buckling behavior occurs. With the increase in the end displacement of components L140 × 14G76SR75-1712, L140 × 14G76SR75-855, and L140 × 14G76SR75-570, the stress concentration and slight local deformation first appeared at the connection between the angle steel and the end plate. As the displacement of the end plate continues to increase, the middle part of the member is deformed, but the deformation speed is significantly lower than that of the original angle steel member. After reinforcement, the member shows certain ductility characteristics. The angle steel member

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**Figure 6:** Member buckling shape (L63 × 5 mm). (a) L63 × 5G0SR75-0. (b) L63 × 5G34SR75-587. (c) L63 × 5G34SR75-295. (d) L63 × 5G34SR75-235.

**Figure 7:** Force-displacement curve (L100 × 10 mm).
Figure 8: Member buckling shape (L100 × 10 mm). (a) L100 × 10G0SR75-0. (b) L100 × 10G57SR75-1150. (c) L100 × 10G57SR75-575. (d) L100 × 10G57SR75-385.

Figure 9: Force-displacement curve (L140 × 14 mm).
L140 × 14G0SR75-0 has no steel pipe to constrain its overall buckling behavior; so the member cannot develop local buckling deformation. It shows obvious buckling characteristics and has poor ductility.

The improvement effect of the bearing capacity of the new reinforcement scheme is greatly affected by the distance between the fixtures; the smaller the distance between the fixtures is, the more obvious the effect of reinforcement. When the effect of reinforcement is considered, the smaller the fixture spacing is, the better the bearing capacity and ductility of the reinforced components can meet engineering requirements. Considering the economics of reinforcement and the convenience of construction, the larger the distance between the fixtures is, the lower the construction cost is, and the better the convenience of use is. Therefore, it is necessary to find a balance between the effect of reinforcement and economy.

The cross section of the angle steel member is L63 × 5 mm, and when the distance between the fixtures is less than 295 mm, the bearing capacity of the components cannot be effectively improved as the distance is further reduced. At this time, the ratio of the distance between the fixtures and the width of the angle steel legs is 4.68. In this paper, it is believed that when the angle steel member with a cross section of L63 × 5 mm is reinforced, the fixture spacing can be taken as 4.68 times the width of the angle steel leg to obtain good reinforcement and economy effects. The cross section of the angle steel is L100 × 10 mm. When the distance between the fixtures is less than 575 mm, the effect of increasing the bearing capacity is no longer obvious. When the distance between the fixtures is greater than 575 mm, the ductility of the reinforced member is not significantly improved. Considering bearing performance after reinforcement and the economy of reinforcement, it is considered reasonable to select the fixture spacing as 5.75 times the width of the angle steel legs. When the cross section of the angle steel is L140 × 14 mm, the distance between the fixtures is 6.11 times the width of the angle steel leg, which can meet the requirements of bearing capacity improvement and economy.

Based on the above analysis, a reasonable fixture spacing of an angle steel member with different specifications is different, and it has a proportional relationship with the leg width of the reinforced angle steel. Through the simulation of three different specifications of angle steel, the results indicate that when using this new reinforcement scheme to reinforce the transmission tower angle steel, the distance between the fixtures should not be greater than 5.00 times the width of the reinforced angle steel leg.

**Figure 10**: Member buckling shapes (L140 × 14 mm). (a) L140 × 14G0SR75-0. (b) L140 × 14G76SR75-1712. (c) L140 × 14G76SR75-855. (d) L140 × 14G76SR75-570.
3.2. Influence of the Angle Steel Section Size. The new reinforcement scheme demonstrates a certain difference in the effect of reinforcement of different specifications of angle steel. Table 2 shows the improvement level of the bearing capacity of different specifications of angle steel. The slenderness ratio of the reinforced angle steel remains unchanged, the relative size of the steel pipe and the angle steel is maintained in the same range, and the maximum bearing capacity of the reinforced angle steel is taken. Comparing the improvement rate of the bearing capacity of different specifications of angle steel, the minimum value of the improvement rate of bearing capacity is 32.2%. It can be considered that this reinforcement scheme has a significant reinforcement effect on the angle steel member with the section size from L63 × 5 mm to L140 × 14 mm. There is a large fluctuation in the bearing capacity increase rate of angle steel of different specifications. It is believed that the reinforcement scheme is affected by the size effect to a certain extent. When the size of the reinforced angle steel is too small or too large, it will have a certain impact on the reinforcement effect. However, the ideal reinforcement effect can still be achieved by properly setting the distance between the fixtures. It can be considered that this reinforcement scheme has a good reinforcement effect on angle steel with different cross-sectional sizes and has strong versatility.

As shown in Figure 11, the larger the distance between the fixtures, the greater the load on the fixtures, the greater the stress on the fixtures, and the more obvious the strain. When the angle steel is subjected to pressure and overall buckling occurs, the fixture will tightly connect the steel pipe and the angle steel to realize the effect of constraining the buckling of the angle steel with the flexural bearing capacity of the steel pipe. The fixtures need to bear the force of the steel pipe and the angle steel at the same time. Therefore, to ensure the common deformation of the steel pipe and the angle steel, damage to the fixtures needs to occur after damage to the angle steel or the steel pipe. In the parameter study of this paper, the thickness of the steel plate of the fixture is 6 mm. Neither the fixture nor the bolt is damaged before the large buckling deformation of the component occurs.

3.3. Slenderness Ratio of Angle Steel. Angle steel members have different slenderness ratios. To explore the influence of different slenderness ratios on the reinforcement effect of the new reinforcement scheme, four kinds of angle steel members with different slenderness ratios were selected for reinforcement. The section size of the strengthened angle steel is L100 × 10 mm, and the fixture distance is 575 mm. A steel pipe with an external diameter D = 57 mm and a wall thickness t = 4 mm is selected.

As shown in Figure 12, with an increase in the slenderness ratio of the angle steel members, the buckling bearing capacity of the original member decreases gradually. The buckling capacity of angle steel reinforced by the new reinforcement scheme is clearly improved, and the improvement rate of bearing capacity α is different under different slenderness ratios. The bearing capacity of strengthened members is different. By increasing slenderness ratio, the bearing capacity of the strengthened members also shows a descending trend, but the increase rate of the bearing capacity of the angle steel after reinforcement increases, indicating that the larger the slenderness ratio is, the more obvious the reinforcement effect of the new reinforcement scheme is, and the higher the bearing capacity improvement rate is.

This reinforcement scheme has a good reinforcement effect on angle steel members with slenderness ratios from 55 to 115. The greater the slenderness ratio is, the more obvious the reinforcement effect is.

The buckling modes of components with different slenderness ratios are different. When the slenderness ratio of the angle steel is small, the component first deforms locally near the end and continues to increase with the displacement of the end, and the component begins to demonstrate an overall buckling shape, as shown in Figure 13 for components L100 × 10G57SR55-575 and L100 × 10G57SR75-575. When the slenderness ratio of angle steel increases, there is no obvious local buckling phenomenon. With the increasing end displacement, the component presents overall buckling failure.

In summary, the slenderness ratio of components has a great influence on the reinforcement effect. The larger the slenderness ratio is, the higher the improvement rate of the bearing capacity of the new reinforcement scheme is, and the minimum value of the improvement rate of the bearing capacity is 25.4%. The new reinforcement scheme has a good effect on all kinds of slenderness ratio components.

3.4. Effect of Different Specifications of Steel Pipe on Reinforcement. When steel pipes with different cross-sectional sizes are used to reinforce a specific angle steel component, a steel pipe with a small cross-sectional size ensures that the reinforcement scheme has good economy and low reinforcement costs. The relative size of the steel pipe and the reinforced angle steel member will also affect the reinforcement effect.

The reinforced angle steel section is selected as L100 × 10 mm, the slenderness ratio of the angle steel is 75, and the fixture distance is determined to be 575 mm. Six kinds of steel pipes were used for the reinforcement. The six component numbers are L100 × 10G40SR75-575, L100 × 10G45SR75-575, L100 × 10G50SR75-575, L100 × 10G55SR75-575, L100 × 10G63SR75-575, and L100 × 10G70SR75-575.

As shown in Figure 14, compared with the original component, the bearing capacity of the component after reinforcement shows different degrees of improvement. The external diameter D of the steel pipe section used in component L100 × 10G40SR75-575 is 40 mm, and the wall thickness t = 2.5 mm. Compared with the original angle steel member, the buckling bearing capacity increased by 25.1%. The ratio of the external diameter of the steel pipe to the width of the reinforced angle steel is 0.4, the ratio of the wall thickness of the steel pipe to the thickness of the angle steel component is 0.25, and the cross-sectional area of the steel
Table 2: Bearing capacity comparison table.

| Angle steel type | Bearing capacity before reinforcement (kN) | Bearing capacity after reinforcement (kN) | Increase amplitude (kN) | Increase rate $\alpha$ (%) |
|------------------|-------------------------------------------|------------------------------------------|------------------------|---------------------------|
| L63 $\times$ 5 mm | 127.51                                    | 185.33                                   | 57.82                  | 45.3                       |
| L100 $\times$ 10 mm | 354.96                                  | 619.90                                   | 264.94                 | 74.6                       |
| L140 $\times$ 14 mm | 693.75                                  | 917.26                                   | 223.51                 | 32.2                       |

Figure 11: Fixture stress contours. (a) L100 $\times$ 10G57SR75-1150 end fixture. (b) L100 $\times$ 10G57SR75-575 end fixture. (c) L100 $\times$ 10G57SR75-385 end fixture. (e) L100 $\times$ 10G57SR75-575 middle fixture. (f) L100 $\times$ 10G57SR75-385 middle fixture.

Figure 12: Effect of improving the bearing capacity with different slenderness ratios.
Figure 13: Buckling patterns of the members with different slenderness ratios. (a) L100 × 10G57SR55-575. (b) L100 × 10G57SR75-575. (c) L100 × 10G57SR95-575. (d) L100 × 10G57SR115-575.

Figure 14: Effect of the different specifications of steel pipes on the reinforcement.
pipe is 15.3% of the cross-sectional area of the angle steel member. The steel pipe utilization rate is defined as $\beta$.

$$\beta = \frac{\alpha \cdot a_2}{a_1}, \quad (2)$$

where $\beta$ is the steel pipe utilization rate, $\alpha$ is the angle steel bearing capacity improvement rate, $a_1$ is the ratio of the steel pipe section area, and $a_2$ is the angle steel sectional area.

The utilization ratio of steel pipe $\beta$ is the relative relationship between the lifting ratio of angle steel bearing capacity $\alpha$ and the ratio of steel pipe to the angle steel area. The larger the angle steel bearing capacity increase rate $\alpha$ is, the better the reinforcement effect is. The cross-sectional area ratio of the steel pipe to angle steel reflects the economy of the new reinforcement scheme. The smaller the area ratio is, the lower the reinforcement cost is. The bearing capacity improvement level and reinforcement cost of angle steel are opposite to each other. When other conditions are the same, the larger the bearing capacity improvement rate $\alpha$ is, the larger the cross-sectional area of the steel pipe is needed, and the higher the reinforcement cost is. The smaller the ratio of the cross-sectional area of the steel pipe to the angle steel is, the lower the reinforcement cost is, but the increase rate of the bearing capacity decreases. The utilization ratio of steel pipe $\beta$ reflects the relationship between the bearing capacity improvement and the reinforcement economy. When the slope of the curve is greater than 0, the growth rate of the bearing capacity improvement rate is greater than the growth rate of the ratio of the section area of the steel tube to the angle steel. Additionally, the larger the slope is, the more obvious the effect of increasing the section area of the steel pipe on the bearing capacity of the angle steel is. When the slope of the curve is less than 0, the increase in the bearing capacity lags behind the growth rate of the ratio of the cross-sectional area of the steel pipe and the angle steel. The smaller slope indicates that increasing the section of the steel pipe has less influence on the bearing capacity of the members.

When selecting steel pipes for reinforcement, it is necessary to make full use of the rising section of the steel pipe utilization curve to avoid excessive reinforcement costs caused by excessive falling sections. As shown in Figure 15, in this study, it is considered that the ratio of the sectional area of the steel pipe and the angle steel corresponding to the top of the rising section is reasonable. The optional section specifications of the steel pipe and angle steel are fixed. Therefore, considering the practical application of engineering, a reasonable ratio range of the cross-sectional area of the steel pipe and angle steel member should be given. The maximum value of steel pipe utilization rate $\beta$ is 2.35, and the minimum value is 1.39. When steel pipe utilization rate $\beta$ is greater than 2.0, it can be considered that the steel pipe utilization rate is at a high level. When the steel pipe utilization rate $\beta$ is greater than 2.0, the corresponding interval of the ratio of the cross-sectional area of the steel pipe to the angle steel component is 17–34%. It can be considered that the reasonable interval of the ratio of the cross-sectional area of the steel pipe to the angle steel is 17–34%. When the increase in the steel pipe utilization rate is fully utilized, the optimal interval of the ratio of the steel pipe to the angle steel component is 23–34%. This optimal interval not only ensures a high utilization rate of the steel pipe, but also makes the bearing capacity improvement rate as high as possible. When the original angle steel member with a cross-sectional size of L100 $\times$ 10 mm is reinforced, the ratio of the cross-sectional area of the selected steel pipe to the cross-sectional area of the angle steel component is within the range of 23–34%, which can guarantee the reinforcement effect and the economy of the reinforcement scheme.

As shown in Figure 16, when the section size of the steel pipe is $D = 70$ mm and the wall thickness is $t = 5.0$ mm, local buckling occurs. When the section size of the steel pipe is $D = 57$ mm and the wall thickness is $t = 4.0$ mm, local buckling occurs slightly in the early stage, and an obvious global buckling characteristic occurs by increasing end displacement. When the section size of the steel pipe is $D = 50$ mm and the wall thickness is $t = 3.0$ mm, the component presents overall buckling characteristics. When the section size of the steel pipe is $D = 40$ mm and the wall thickness is $t = 2.5$ mm, the component also presents overall buckling characteristics. The bending capacity of the steel pipe determines the buckling capacity and buckling form of the angle steel component. When the flexural rigidity of steel pipes with high section sizes is larger, the lateral constraint provided to the original angle steel component is stronger. At this time, the force of the angle steel member on the steel pipe cannot make the steel pipe bend as a whole, and the buckling capacity of the angle steel member is improved. The simulation results show that the larger the size of the steel pipe is, the better the ductility of the angle steel member during buckling is, but the improvement of this ductility is limited. As shown in Figure 14, the force-displacement curves of members L100 $\times$ 10G57SR75-575, L100 $\times$ 10G63.5SR75-575, and L100 $\times$ 10G70SR75-575 decrease slowly with the increasing end displacement after the buckling load reaches a peak. The ductility of the original angle steel member and the member strengthened with a 40 mm external diameter of steel pipe and $t = 2.5$ mm wall thickness is poor. The bearing capacity of the member decreases rapidly with increasing end position after the buckling point. When the steel pipe size increases to an external diameter of $D = 57$ mm and a wall thickness of $t = 4.0$ mm, the ductility of the component is significantly improved. With the increase in the steel pipe size, the ductility of component L100 $\times$ 10G70SR75-575 shows no significant improvement compared with that of component L100 $\times$ 10G57SR75-575. This indicates that when the steel pipe size increases to a certain value, the improvement in the ductility of the component by continuously increasing the section size of the steel pipe gradually decreases.

Combined with Figure 16, it can be found that the postbuckling ductility is related to the buckling characteristics. The overall buckling deformation of the member is restrained at the initial buckling stage, and local deformation occurs, which can effectively improve the ductility of the member at the initial buckling stage.
Through the analysis of various components, considering the reinforcement effect and cost of the new reinforcement scheme, it is considered that it is reasonable to select the cross-sectional area of the steel pipe as 23–34% of the cross-sectional area of the angle steel member. At this time, the reinforcement cost is low, the reinforcement effect is remarkable, and the component shows good ductility when damaged.

4. Conclusions

In this paper, a new buckling bearing capacity enhancement scheme is proposed. The steel pipe is used as the auxiliary material, and the steel pipe is connected with the angle steel member through the clamp, so as to avoid the adverse effect of the bolt connection and welding on the bearing capacity of the original angle steel. The effects of fixture spacing, angle
steel size, member slenderness ratio, and steel pipe specification on the reinforcement effect were studied through numerical analysis. The following conclusions are drawn.

1. The reinforcement effect is highly correlated with the fixture distance. The smaller the fixture distance is, the greater the improvement rate of the bearing capacity of the component is and there is a reasonable range of fixture spacing.

2. There is a correlation between the reasonable distance and the width of the reinforced angle steel limb. When the ratio of the fixture distance to the width of the reinforced angle steel limb is less than 5, it is considered that the reinforcement scheme has a good bearing capacity improvement effect, and the bearing capacity improvement rate is greater than 50%.

3. The slenderness ratio of angle steel affects the reinforcement effect of the new bearing capacity improvement scheme. The larger the slenderness ratio of angle steel is, the larger the bearing capacity improvement rate is, and the more obvious the bearing capacity improvement effect is.

4. Different steel pipe specifications affect the reinforcement effect of the new scheme. Considering the effect of reinforcement and the economy, it is considered reasonable that the sectional area of the circular steel pipe is 23–34% of the angle steel.

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 they have no conflicts of interest.

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