Mechanical properties analysis of Angle steel connector of composite bridge with corrugated steel webs

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Abstract. The finite element software Midas FEA was used to simulate and calculate the ultimate bearing capacity, von Mises stress and load-slip curves of the Angle steel connector specimen of the composite bridge with corrugated steel webs. And the ultimate bearing capacity obtained by numerical simulation is compared with the calculated value of the bearing capacity of Angle steel connectors in each specification. The results show that when the ultimate bearing capacity of the specimen is reached, most of the Angle steel is in a state of buckling, all the steel bars are in a state of buckling with deformation, and the concrete pin in the hole is partially damaged. In the specifications, the calculation formula of bearing capacity of Angle steel connector is conservative, the main reason is that the influencing factors of ultimate bearing capacity of Angle steel connector are not comprehensive enough, and the existing formula needs to be further revised.

1. Introduction
Corrugated steel web composite bridge, as a new type of steel-composite bridge structure, has developed rapidly in recent years. Different from traditional prestressed concrete Bridges, corrugated steel webs composite Bridges use corrugated steel plates instead of concrete webs, and use shear connectors welded to the upper and lower flanges of corrugated steel plates to realize the connection with the upper and lower concrete flanges[1-3]. Compared with the traditional prestressed concrete bridge, the concrete flange of the composite bridge with corrugated steel webs bears the bending moment and corrugated steel webs bears the shear force, which make the overall structure bear clear and reasonable forces. This structure reduces the dead weight and improves the utilization rate of the material[4-6]. The structure of corrugated steel web composite box girder is shown in Figure 1[1].

The main function of shear connector is to connect upper and lower concrete flange plates, transfer horizontal shear force and resist corner bending moment[7-9]. At present, there are three types of shear connectors for composite Bridges with corrugated steel webs: embedded type, flange type and hybrid type. The Angle steel connector is a form of flange shear connector, which is composed of an Angle steel welded to the steel plate flange, a u-shaped steel bar and a perforated steel bar. The Angle steel connector is shown in Figure 2[1].
In this paper, the finite element software Midas FEA is used to simulate the pushed-out specimens of Angle steel connector, and the ultimate bearing capacity and von Mises stress of pushed-out specimens are obtained. The simulation results are compared with the calculation results of the bearing capacity formula of Angle steel connector in the existing specification to verify the effectiveness of the formula.

2. Finite element model and material setting

Finite element software Midas FEA was used to numerically simulate the pushed-out specimen of Angle steel connector. The specimen structure of Angle steel connector is shown in Figure 3. The Angle steel with the hole is welded to both sides of the I-beam, the hole is provided with perforating steel bar, and the concrete block is poured on the outside of the Angle steel. The size of Angle steel is 200*90*90mm, the thickness is 12mm, Q235 material, the hole aperture is 40mm. The perforated steel bar is made of HPB235 material with a diameter of 16mm. The outer concrete is C45 grade, the designed value of axial compressive strength is 20.5Mpa, and the designed value of tensile strength is 1.74Mpa. The I-beam is made of Q345 material.

In the modeling, the metal material is simulated by the von Mises model, and the concrete material is simulated by the total strain fracture model. The constitutive relationship of the total strain fracture model is shown in Figure 4. The concrete setting of the model is that the concrete bottom of the pushed-out specimen is set as fixed nodes. Set welding contact between Angle steel and I-beam. The vertical downward uniformly distributed load is applied to the top of the I-beam to achieve the push-out effect. The model is shown in Figure 5.
3. Comparison between numerical simulation and the existing standard calculation formula of ultimate bearing capacity

According to the finite element numerical simulation, the ultimate bearing capacity of the pushed-out specimen of the Angle steel connector is 1446KN, and the corresponding von Mises stress cloud diagram is shown in Figure 6. According to the stress cloud diagram, when the ultimate bearing capacity of the specimens is reached, the I-beam and its welded Angle steel have obvious downward displacement. Most of the Angle steel has reached the yield state. All the steel bars in the hole reach the yield state and displacement occurs. The concrete in the hole is partially damaged due to the displacement of steel bars through it. Figure 7 shows the load-slip curve obtained by simulating the pushed-out specimen of Angle steel connector. It is concluded that the load-slip curve of the specimen can be roughly divided into three parts: linear stage, nonlinear stage and failure stage. The stage of 0KN to 450KN is a linear stage, in which the load-slip curve is a straight line and the slip is small. About 450KN to 1100KN is a nonlinear stage. In this stage, the image presents a curve with changing slope, and the amount of slip increases with the increase of load. After 1100KN is the failure stage. In this stage, a small amount of load is added, and the amount of slip will increase greatly. When the load reaches 1446KN, the failure of the specimen is pushed out.
The numerical simulation results of the ultimate bearing capacity of the Angle steel connector are compared with the calculated bearing capacity of Angle steel connector in the existing specifications. The results are shown in table 1. The calculation formula of relevant specifications is shown in table 2.

![Figure 6. Von Mises stress image of finite element model.](image)

![Figure 7. The load-slip of push-out specimens.](image)

### Table 1. The comparison of bearing capacity calculation results.

| source               | Calculated value (KN) | Simulation value/ Calculated value |
|----------------------|-----------------------|-----------------------------------|
| Finite element simulation | 723                   | 1.00                               |
| CJJ/T 272-2017[10]    | 277                   | 2.61                               |
| Euro Code 4[11]       | 210.1                 | 3.44                               |
| AISC 360-05[12]       | 287.5                 | 2.51                               |
Table 2. The formula of bearing capacity of Angle steel connector.

| Source                  | Formula of shear bond bearing capacity of Angle steel | Formula annotation |
|-------------------------|------------------------------------------------------|--------------------|
| CJJ/T 272-2017[10]     | $Q_u = \min(Q_{u1}, Q_{u2})$                         | $f_{cd}$ - Compressive strength of concrete |
|                         | $Q_{u1} = A_c f_{cd} / 1.5$                          | $A_c$ - Bearing area of Angle steel |
|                         | $Q_{u2} = \sum aL (f_y / \sqrt{3})$                 | $a$ - Theoretical weld thickness, $L$ - Length of Angle steel, $f_y$ - Yield strength of steel |
| Euro Code 4[11]         | $P_{Rd} = \frac{10 \times l \times h^2 \times f_{ck}^2}{r_v}$ | $l$ - Channel steel limb width, $h$ - Channel steel limblong, $f_{ck}$ - Concrete design standard strength, $r_v$ - Safety factor, take 1.25 |
| AISC 360-05[12]         | $Q_u = 0.588 t L \sqrt{f_c}$                        | $t$ - The thickness of the Angle steel, $L$ - Length of Angle steel, $f_c$ - Compressive strength of concrete |

According to table 1, the calculation results of the formulas for Angle steel connector given in the current specification are all lower than the numerical simulation results, and the simulation results are about 2 to 3 times of the calculation results. On the one hand, the formula itself has a lot of safety reserves; on the other hand, in each formula only the Angle steel length, Angle steel thickness and concrete compressive strength and other aspects of the discussion, but the hole through the steel bar, the hole concrete pin and other factors are not considered. It can be seen from the finite element model stress cloud Figure 6 that, when the ultimate bearing capacity is reached, the steel bar in the hole is bent and deformed, while the concrete pin in the hole is partially damaged. This shows that the steel bar and concrete pin in the hole bear a strong shear force, which is necessary to be discussed when calculating the ultimate bearing capacity of the Angle steel connector.

### 4. Conclusion

1) Numerical simulation was carried out on the pushed-out specimens of Angle steel connector by using the finite element software Midas FEA, and the ultimate bearing capacity was obtained to be 1446KN. The results of the von Mises stress show that most of the Angle steel reaches the yield state when the ultimate load is reached. The steel bar through the hole completely reaches the yield state and deformation occurs. The concrete pin in the hole is partially damaged.

2) The finite element numerical simulation results are compared with the calculation results of bearing capacity of the Angle steel connector in each specification, and the simulation results are 2 to 3 times of the calculated results.

3) The formulas for calculating the bearing capacity of Angle steel connector in each specification, on the one hand, have a high safety reserve; on the other hand, they only discuss the geometric parameters of Angle steel and the compressive strength of concrete, but do not discuss the shear action of steel bars through holes and concrete pins in holes, so it is necessary to correct the formulas appropriately.
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