

Study on Shearing Characteristics of Circumferential Joint Rebate of Stagger-Jointed Shield Tunnel

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Abstract. At present, the design and construction of shield tunnels often adopt stagger-jointed form with rebate, and improving the mechanical properties of rebate is the key to solving the problem of leakage of tunnel structure and other diseases. This paper aimed at circumferential joint rebate of staggered shield tunnel segment, established the local model of discontinuous contact of three-dimensional solid joint to analyse the influence of rebate and the length and inclined angle of it on shear resistance of joint. The result shows five points: (1) When the segment joint is sheared, the greater the axial force of the joint, the stronger the frictional shear resistance. (2) Setting rebate in joints can reduce the number of dislocations in the stage of rapid development of dislocation and increase the shear resistance of joints. (3) The length of rebate has little influence on the shear strength of joints. (4) The angle of inclined plane of rebate has a great influence on the shear resistance of joint. The smaller the angle of inclined plane, the larger the peak shear force and the corresponding dislocation, while the greater the local stress. (5) When the inclined angle increases, the stress of rebate is more uniform, which can prevent the damage of rebate.

1. Introduction

Shield tunnelling is a commonly used tunnel form in urban metro, using assembled lining as a long-term structural carrier. There are two types of lining ring assembling, the through joint and the staggered joint. General segment is usually assembled by staggered joints, which can not only make the stiffness distribution of lining circumferential joints uniform, reduce the deformation of joints and the whole structure, but also be beneficial to waterproof structure and control of shield axis. [1] Therefore, the research on staggered shield tunnel segment is of great significance.

In view of the rebate of circumferential joint assembly shield tunnel segment annular joint, many domestic scholars have carried out relevant research. Wang Tan [2], Zhang Weixi [3], Teng Li [4], Zhu Yaohong et al. [5] studied the staggered shield tunnel segment, which showed that the ability of controlling structural deformation of staggered joint segment was enhanced due to the assembly effect. Zhong Xiaochun [6], Yang Zhao et al. [7] pointed out that the staggered joint assembly method can provide effective constraints on the joint and ensure the long-term waterproof effect of the tunnel. Huang Zhonghui et al. [8] pointed out that the existence of rebate can improve the longitudinal stress state of the tunnel. Zhu Yaohong et al. [10] studied the shear behavior of rebate in Ningbo rail transit shield tunnel. Huang Jun [11] research reduces the breakage of rebate in small radius curves during shield construction in Hangzhou Metro. Jiang Shouchao et al. [12] discussed the performance of rectangular shield joints under the conditions of composite shear resistance, considering installation error and rebate shear resistance alone respectively. In combination with the Shiziyang Tunnel Project of Guangzhou-Shenzhen-Hong Kong High Speed Railway, Feng Kun et al. [13] carried out tests to show the bending stiffness of segment joints under high pressure. In addition, Xiao Mingqing et al. [14] invented a circular rebate shear structure between segments of shield tunnel. Shen Xiufang et al. [15]



designed a concave-convex connection structure between lining segment and inner lining in shield tunnel. Existing studies only focus on staggered shield tunnel segment, but few on the stress characteristics of circumferential joint rebate itself and its size. However, the opening of joints affects the overall force of the segment, so improving the mechanical performance of the circumferential joint rebate is the key to solve the problems of leakage of tunnel structure.

Aiming at the shield tunnel joint with 400 mm segment thickness, a three-dimensional solid discontinuous contact local model of the joint is established, and then the influence of rebate itself and length and inclined angle of it on shear resistance of joint is researched.

2. Finite Element Model of Three-Dimensional Local Joints

The joint structure of shield tunnel is complicated. There are complex structures such as connecting bolts and sealing gaskets, and its mechanical characteristics are obviously non-linear. In order to simulate the real impact of joint components on nearby concrete, a three-dimensional discontinuous contact local model of joint was established by ABAQUS finite element software, which considers the contact between segments and bolts to achieve more accurate simulation. The local model of discontinuous contact of three-dimensional solid joint is shown in Fig 1.

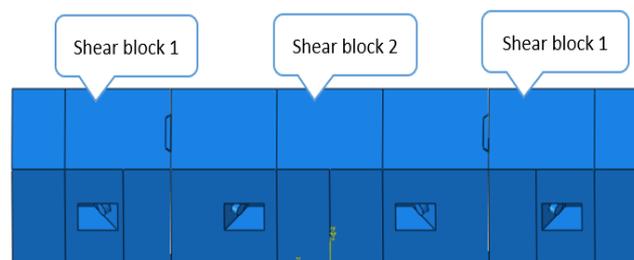


Figure 1. Local Finite Element Model of Joints

3. Geometric Model

Based on the design scheme of shield tunnel segment in a urban rail transit, a geometric model is established, in which the diameter of bolt hole is 36 mm, the diameter of bolt is 30 mm, the thickness of segment is 400 mm, and the length is 500 mm. The geometric structure of rebate is shown in Figure 2, among which the concave tenon length of rebate is 165 mm, and the inclined angle is 55 degrees.

In order to study the change of shear resistance of joints under the change of rebate size, the middle part of rebate was lengthened to 195mm and shortened to 135 mm on the basis of the design scheme. In addition, the inclined plane angles of rebate are transformed to 73 degrees and 33 degrees respectively.

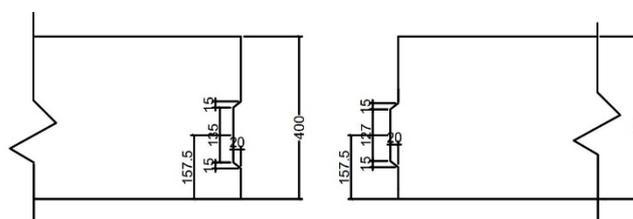


Figure 2. Size Diagram of Rebate

4. Constitutive Properties and Parameters of Materials

The constitutive relationship of concrete is based on the plastic damage model of concrete in ABAQUS, and the elastic damage model of isotropy is used to simulate the inelastic behavior of concrete in combination with isotropic tension or compression plasticity.

In the elastic stage, concrete damaged plasticity model (CDP model for short) uses elastic model to describe the mechanical properties of materials. After entering the damage stage, the relationship between the elastic modulus of the damaged CDP model is as follows:

$$E=(1 - d)E_0 \tag{1}$$

In the formula, E_0 is the initial modulus of elasticity and d is the plastic damage factor d_t or d_c under tension or compression. The range of plastic damage factor d is 0~1. 0 indicates that the material has not been damaged, and 1 indicates that the strength of the material has been completely lost. According to the user-defined nominal stress-strain curves of concrete, they are transformed into the parameters needed in ABAQUS through the principle of energy equivalence. Tensile damage parameters are input into ABAQUS in the form of $\sigma_t - \varepsilon_t^{ck}$ and compressive damage in the form of

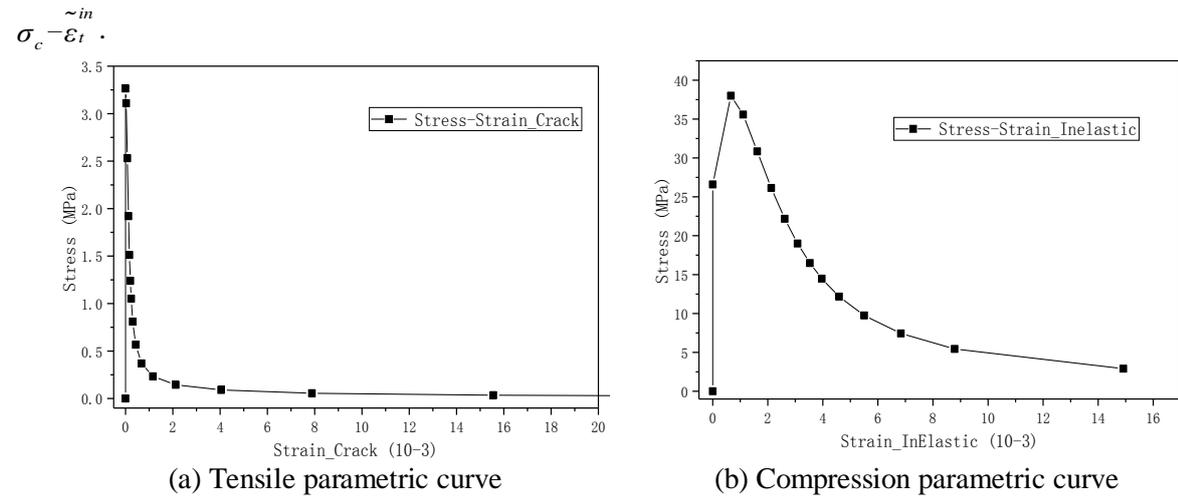


Figure 3. Constitutive Curve of C50 Concrete Material

The values of other constitutive parameters for elastic-plastic damage of concrete are shown in Table 1.

Table 1. Other Constitutive Parameters

dilatancy angle	flow potential skewness	σ_b/σ_c	Kc	viscosity coefficient
38	0.1	1.16	0.6666	0.0005

The bolt constitutive model is simplified to double folded line constitutive model. The elastic modulus in elastic stage is 210 GPa, Poisson's ratio is 0.2, and the elastic modulus after yield is 2.1 GPa. The 5.8 grade bolt material has yield strength of 400 MPa and an ultimate tensile strength of 500 MPa, the constitutive curve is shown in Figure 4.

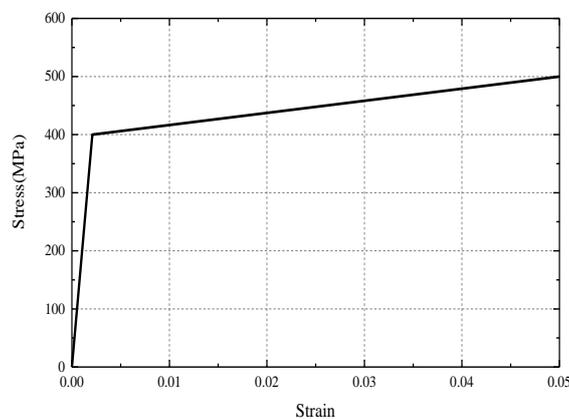


Figure 4. Constitutive Curve of Bolt Material

5. Load and Boundary Conditions

In order to compare and analyze the influence of rebate on the shear properties of joints, the shear properties of two kinds of joints were simulated and calculated: single rebate, rebate and bolt joint. Three working conditions with axial force of 100kN, 300kN and 500kN are selected. Firstly, load-controlled loading mode is used to load horizontal force F on both ends of two shear piece 1 to simulate the axial force at the joint, and then displacement-controlled loading mode is used to load vertical force P on the top of shear piece 2 to simulate the joint being gradually sheared.

When horizontal force F is applied, the displacement of bottom X, Y and Z directions of shear piece 2 and bottom Y and Z directions of shear piece 1 in finite element model are constrained. While the vertical force P is loaded, the displacement in X, Y and Z directions of the bottom of shear piece 1 and the displacement in X and Z directions of the bottom of shear piece 2 are restrained.

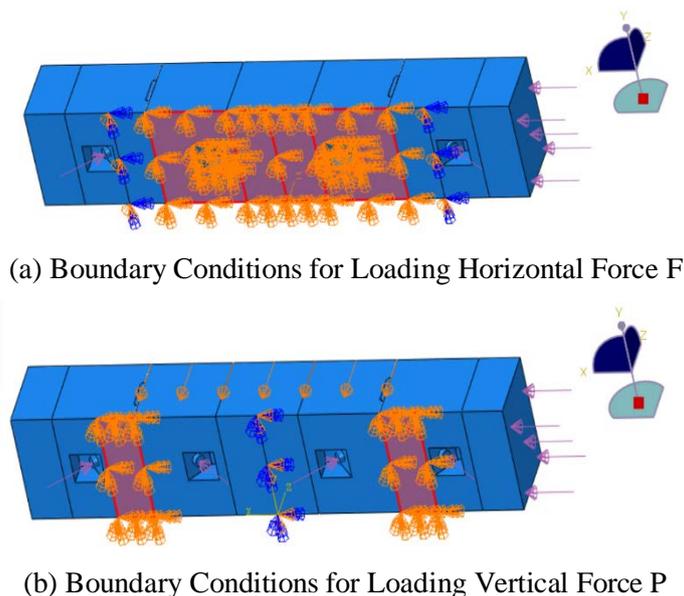


Figure 5. Boundary Conditions

Considering the large displacement of joint contact and bolt segment contact in joint test, finite slip is chosen as contact tracking method in this study. In the mechanical behavior of model contact surface, the normal contact behavior is hard touching, and the tangential contact behavior is Coulomb friction contact. Through the compression and shear tests of concrete interface, the static friction coefficient and dynamic friction coefficient of concrete contact surface are 0.5-0.7 and 0.45-0.67 respectively. Therefore, the friction coefficient between the concretes in this model is 0.5, and the friction coefficient between the bolts is 0.3.

6. The Influence of Rebate

The shear-dislocation curve only with bolts is calculated as shown in Fig 6. There are three stages in the curve: the stage of shear resistance of friction, the stage of rapid development of dislocation, and the stage of shear resistance of friction with bolts and rebate. From the graph, it can be seen that the size of the axial force has a significant impact on the shear resistance of the joint. The greater the axial force, the stronger the friction shear resistance.

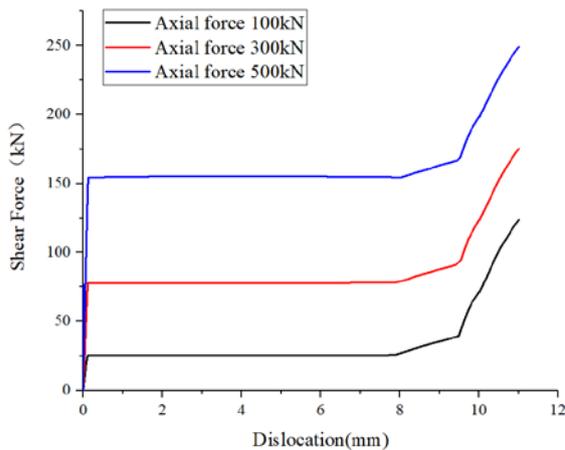


Figure 6. Shear-dislocation Curve of Joint with Bolt

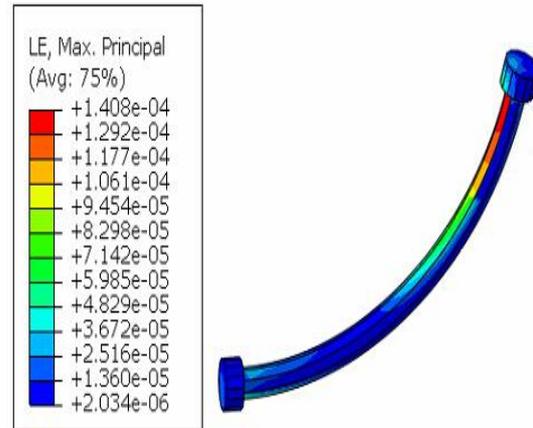


Figure 7. Bolt Strain (300kN)

Under three kinds of axial forces, when the dislocation amounts to 7.74 mm, 7.87 mm and 7.97 mm respectively, the bolt contacts with the bolt hole, and the bolt begins to participate in shear resistance. When the dislocation amounts to 10.4 mm, 10.6 mm and 10.5 mm respectively, the collapsing phenomenon of pore wall concrete has appeared. Taking the case of 300 kN axial force as an example, with the further increase of dislocation, the damage of pore wall concrete continues to develop. The bolts are in the elastic stage during the whole process from dislocation to 11mm. The maximum strain and stress of the bolt are 1.41×10^{-4} and 29.6 MPa when the dislocation is 11 mm, which occur on the arc surface of the bolt, as shown in Figure 7.

The shear-dislocation curves of bending bolt and rebate under different axial load conditions are shown in Fig 7. The curves also have three stages. With the increase of axial force, the maximum shear force at the stage of rapid development of dislocation increases and develops to 4mm. Since then, bolts and rebate have jointly resisted shear, and the shear force increases rapidly with the development of dislocation. In three working conditions, the shear peak values of 1195kN, 1282kN and 1398kN are reached at the dislocation of 4.62mm, 4.75mm and 4.75mm respectively. The increase of axial force can increase the peak shear strength in the third stage, and then enter the softening stage. The smaller the axial force is, the faster the shear strength decreases.

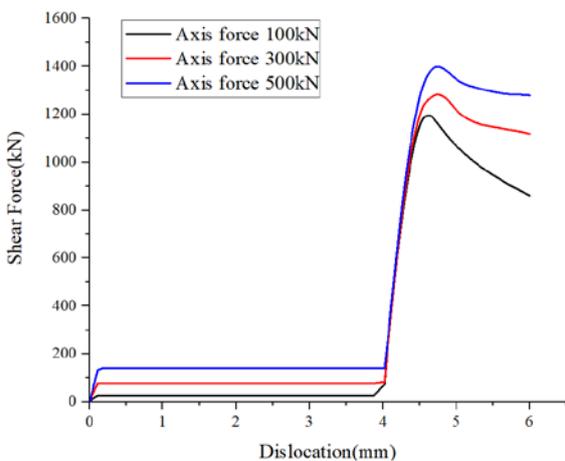


Figure 8. Shear-dislocation Curve of Bending Bolt and Rebate

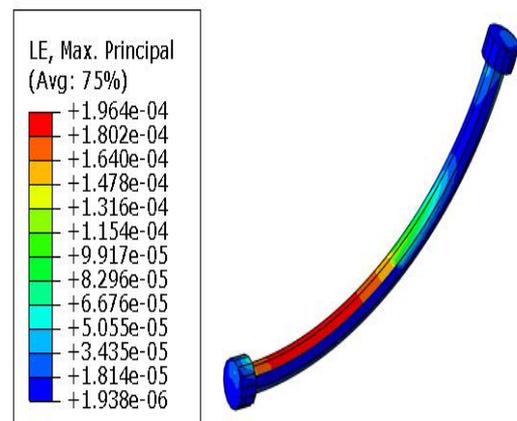


Figure 9. Bolt Strain of Rebate Model (300kN)

When the initial pressure loss of rebate occurs, the dislocation under 100kN, 300kN and 500kN axial force is 4.61mm, 4.57mm and 4.54mm respectively, and the joint shear reaches its peak value.

Taking the 300kN axial force as an example, the bolt is still in the elastic stage when the dislocation develops 6mm. The maximum strain is 1.96×10^{-4} and the maximum stress is 41.2 MPa, which occurs on the inner arc of the bolt shown in Figure 9.

By comparing the shear curves of joints with or without rebate under axial force of 300 kN, it is found that in the second stage, joints without rebate develop rapidly at a lower shear level, and the dislocation can reach 8.1 mm, while in the case of rebate, the staggered stage will enter the third stage when the dislocation reaches 4mm, and the maximum shear force is significantly higher than that of the joint without rebate, as shown in Figure 10.

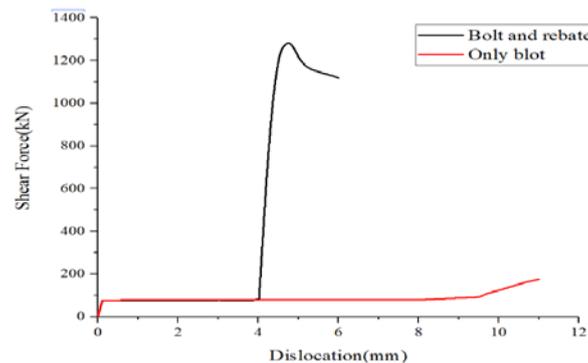


Figure 10. Shear-dislocation Curves of Rebate (300kN)

6.1. The Influence of the Length of Rebate

The shear-dislocation curves calculated by different length of rebate are shown in Figure 11. It can be seen from the graph that changing the length of rebate has little effect on the first and second stages. But the peak value of shear force is slightly different in the third stage that the peak value of rebate model of design length is slightly larger than that of the lengthened and shortened rebate model. In the softening stage, the attenuation of the three models tends to be the same, and the influence of the length of rebate on the curve shape is not significant.

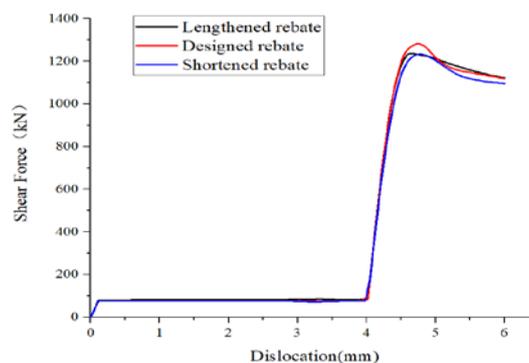


Figure 11. Shear-dislocation Curves of Different Length of Rebate

According to the damage nephogram of rebate, the compressive damage of the lengthened rebate is smaller and distributes along the length direction of rebate, and shortened rebate have large local compression damage and cover the whole tenon, which may damage the whole tenon, while the damage of the designed length model is between the two mentioned above, and its distribution is more uniform but does not penetrate the whole tenon, as shown in Figure 12.

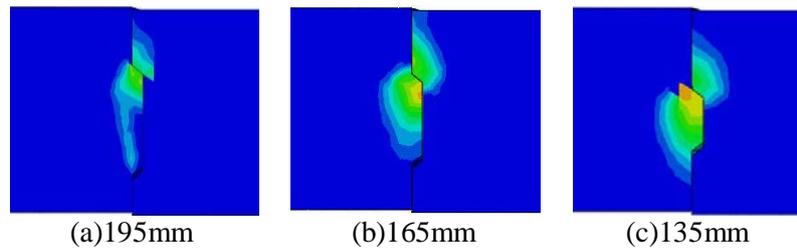


Figure 12. Initial Compressive Damage Morphology of Rebate with Different Lengths

6.2. The Influence of Inclined Plane Angle of Rebate

The shear-dislocation curves calculated from different inclined angles of rebate are shown in Figure 13. It can be seen from the graph that in the third stage, the peak shear force increases with the increase of inclined angle. The peak shear force at 33, 53 and 73 degrees is 1428kN, 1282kN and 1221kN respectively, and the dislocation peak is 5.01mm, 4.76mm and 4.69mm respectively.

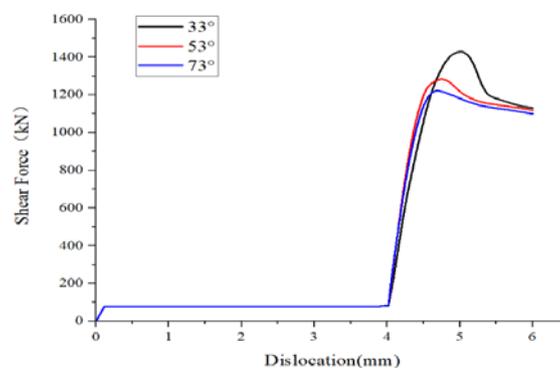


Figure 13. Shear-dislocation Curves of Different Inclined Plane Angles of Rebate

From the damage pattern of rebate, although the peak shear force increases with the decrease of inclined angle, the local damage is relatively increased, which is easy to cause the local damage of rebate. When the inclined angle increases, the range of bearing load concrete at the joint increases and the stress is more uniform, as shown in Figure 14.

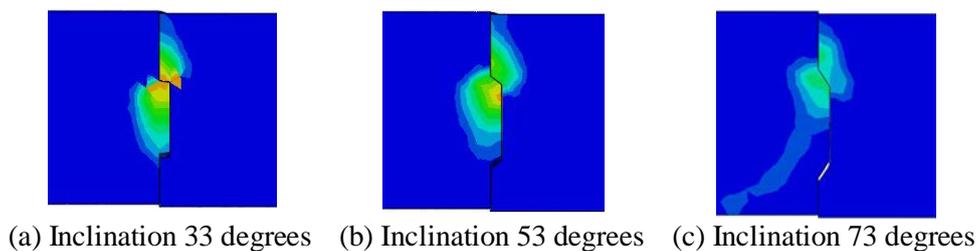


Figure 14. Initial Pressure Loss Form of Rebate with Different Slope Angles

7. Conclusion

This paper aimed at the circumferential joint rebate of staggered shield tunnel segment, established a three-dimensional solid discontinuous contact local model of joint, studied the effects of rebate and length and inclined angle of it on shear resistance of joint. The following conclusions are drawn:

(1) When segment joints are sheared, whether rebate exist or not, the shear-dislocation curves are divided into three stages: the stage of shear resistance of friction, the stage of rapid development of

dislocation, and the stage of shear resistance of friction with bolts and rebate. The magnitude of the axial force has a significant impact on the shear resistance of the joint. The greater the axial force, the stronger the friction shear resistance.

(2) Compared to joints with only bolts, the setting of rebate can reduce the number of dislocation in the second stage of rapid development of dislocation, and the peak shear force in the third stage increases significantly, which can effectively increase the shear resistance of joint and restrain the development of dislocation.

(3) The length of rebate has little influence on the shear resistance of joint, and the design length is reasonable. The angle of inclined plane of rebate has a great influence on the shear resistance of joint. The smaller the angle of inclined plane, the larger the peak shear force and the corresponding dislocation, but the local stress is greater as well. When the inclined angle increases, the force range of rebate is enlarged and the force is uniform, which can prevent the damage of rebate.

8. References

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