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# Characterization of Shear Damage and Channel Reinforcement of Circumferential Joints between Shield Tunneling Segments Based on Numerical Simulation

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Abstract: Shield misalignment is a common problem in shield tunnels, which seriously affects the safety and durability of tunnels. However, at present, there is a lack of research on the influence of shield misalignment on the shear capacity of the circumferential joint structure, and the failure mechanism of the circumferential joint structure before and after reinforcement is not clear. Therefore, this paper simulates the influence of misalignment on the performance mechanism of segmented circumferential connection and the effect of channel reinforcement on the ABAQUS platform. The simulation results are compared with the full-scale test results, and the results show that the shear failure process of the circumferential joint can be divided into three stages under the condition of no reinforcement. In the first stage, the vertical load increases, but the misalignment between the shield tunneling sections is very small. In the second stage, the load almost does not increase, but the degree of misalignment increases. In the third stage, the load-displacement relationship is nonlinear, indicating that the bending bolt has been sheared. Under the condition of unreinforced, the bolt will form two plastic hinges when it fails. After reinforcing the channel, the removal of the bolt forms only one plastic hinge. After channel steel reinforcement, the boundary area between the channel steel web and the steel plate first reaches the ultimate tensile strength of the steel plate, and the failure mode becomes channel steel reinforcement failure. Under the same shear load, the misalignment of the circumferential joint reinforced with channel steel is reduced. In this paper, the misalignment relationship of shear load and the yield of the bending bolt obtained through numerical calculation is consistent with the conclusion of the full-scale test. However, the circumferential connection misalignment obtained via numerical calculation is relatively small. The yield position of the bending bolt is also in good agreement with the test results, and the bolt strain obtained through the test is relatively small.

**Keywords:** misalignment; circumferential joints; channel reinforcement; shield tunneling segments; full-scale test

### 1. Introduction

With the acceleration of urbanization, the urban population is growing rapidly. The problems caused by the expansion of the urban population are gradually exposed, such as insufficient ground space, traffic congestion, and so on. To solve these problems, the construction and operation of subway tunnels using underground space as a channel is becoming increasingly important. The shield tunnel method has been greatly developed because of its advantages of not being affected by weather and having minimal impact on ground traffic and structure [1,2]. The shield tunnel uses the shield tunneling section assembly machine to assemble the shield tunneling section at the end of the shield machine



Citation: Su, H.; Deng, T.; Yang, Z.; Qin, J.; Zheng, L. Characterization of Shear Damage and Channel Reinforcement of Circumferential Joints between Shield Tunneling Segments Based on Numerical Simulation. *Buildings* **2024**, *14*, 540. https://doi.org/10.3390/ buildings14020540

Academic Editor: Marco Di Ludovico

Received: 2 January 2024 Revised: 31 January 2024 Accepted: 5 February 2024 Published: 18 February 2024



**Copyright:** © 2024 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https:// creativecommons.org/licenses/by/ 4.0/). while the shield tunneling machine is tunneling. The shield tunneling section is the main structural component of the shield tunnel. In the same circle of shield tunneling segments, the joints between segments are called longitudinal joints, while the joints between two circles of segments are called circumferential joints (see Figure 1). Longitudinal and circumferential joints are the weak links of shield tunnels [3].



Figure 1. Schematic diagram of shield tunnel joints.

Misalignment is a common phenomenon in shield tunnel construction. Small misalignment may not affect the normal operation of the tunnel, but serious misalignment will lead to cracks, collapse, water leakage, and other secondary disasters at the joints of the shield tunneling section. Reference [4] pointed out that the most common form of shield interval misalignment can usually be divided into longitudinal joints and circumferential joints, as shown in Figure 2. The circumferential joint refers to the misalignment between the longitudinal joints of two segments in the same ring, and the longitudinal misalignment refers to the misalignment between the segments of the shield tunneling. The main reasons for the misalignment of the shield tunneling segment structure include uneven slurry lifting force, loose connecting bolts, excessive ground stacking, and excessive adjustment of the shield machine's attitude or angle. At present, domestic and foreign scholars have carried out various research methods on the misalignment of circumferential joints [5]. They summarized and analyzed the causes, effects, and rules of misalignment.

At present, many scholars at home and abroad have studied the misalignment of shield tunnel sections using different means and summarized and analyzed the causes, effects, and laws of misalignment. In numerical analysis, the Burger-creep viscoelastic CVISC model is used to study the long-term deformation of the existing tunnel [6]. In Reference [7], a two-stage analysis method based on the Tymoshenko beam model and the Kerr foundation model was proposed to estimate the response of the in-service tunnel, including the influence of the shear of the shield tunneling section and the reduction of the stiffness of the circumferential joints. Considering the circumferential joints, a new longitudinal deformation analysis method for shield tunnel is proposed [8]. A series of full-scale circumferential joint tests were carried out in Reference [9], focusing on specimen displacement, anchorage stress, and joint damage mode. According to these experimental phenomena, the compression–shear bearing process of the new joint and the failure mode of the joint structure were analyzed. The size circumferential joint test was carried out in reference [10], during which the specimen displacement, anchorage stress, and joint

damage mode were focused. In Reference [11], a self-made loading device was used to analyze the stress characteristics and failure process of the straight rod circumferential joint of the large section shield tunnel during the pull-out process. Reference [12] studied the cracks of segment lining under the condition of radial misalignment using a scale test. The test results show that the radial misalignment has a significant influence on the crack morphology of segment lining. In particular, different types of radial misalignment will eventually lead to different types of failure evolution, which will eventually lead to different crack morphology of segment lining.



Figure 2. Misalignment type of shield tunneling segments: (a) circumferential misalignment; (b) longitudinal misalignment.

For subway shield tunnels with misalignment, fracture, and blockage, there are generally internal and external management measures in the industry. Internal measures usually use reinforcement materials such as steel bars or aramid fibers to reinforce the damaged area of the shield tunneling section. The external measure involves controlling the grouting pressure by controlling the grouting volume outside the shield tunneling section [13,14]. Based on an actual project of a subway shield tunnel reinforced using aramid fiber fabric, a three-dimensional numerical model is established to explore the effect of aramid fiber fabric on the longitudinal joint of the shield tunneling section under different loads [15]. Reference [16] studied the influence of different grades of fiber-reinforced shield tunneling section lining on the longitudinal joint of the shield tunneling section. Direct shear and bending tests were carried out to obtain the mechanical properties between the reinforced fiber material and the lining interface of the shield tunneling section. In Reference [17], a full-scale test of the flexural bearing capacity of the polypropylene fiber-reinforced concrete shield tunneling section is carried out, and the bearing capacity of the shield tunneling section after fiber reinforcement is significantly improved. The practical application of thin steel plate reinforcement for the shield tunneling section has demonstrated its feasibility [18]. Reference [19] proposed an analysis method based on composite beam theory to predict interface stress. By comparing the interface stress under steel plate and aramid fiber reinforcement, the author concludes that the interface stress at the end of the steel plate is large, and the thickness and elastic modulus of the bonding layer are the main factors affecting the interface stress. In reference [20], shrinkage tests of longitudinal joints of unreinforced and ring-reinforced shield tunnels under superimposed ground loads were carried out. In Reference [21], the cohesive zone model was used to simulate the interface effect between the inner steel ring and the segmented lining and the influence of bond failure between the steel plate and the concrete interface on structural instability failure and the stress pattern of the steel ring under radial load was analyzed. In reference [22], a two-point loading scale test was carried out on the flexural bearing capacity of a single shield tunneling section, and the shield tunneling section was strengthened using a bonding steel plate. The mechanical properties of the shield tunneling section before and after reinforcement were compared, and the reinforcement effect of steel plate reinforcement was evaluated.

The existing literature extensively discusses circumferential misalignment, while circumferential joints under longitudinal misalignment are mainly affected by shear force. Reference [23] studied the circumferential joint of the shield tunneling section connected using oblique bolts. They used mechanical methods to analyze the failure mechanism of circumferential joints. Oblique bolts are often used in practical engineering to construct large-diameter shield tunnels. The shield diameter of a standard subway tunnel is small, and bending bolts are usually used for longitudinal connection. Therefore, it is necessary to further analyze the failure process of the annular joint of the shield tunneling section connected through bending bolts under the action of shear force.

On the other hand, in the field of shield tunnel reinforcement, there are two types of reinforcement methods: temporary reinforcement and permanent reinforcement. Temporary reinforcement mainly uses longitudinal reinforcement ribs made of channel steel to fix the joints of shield tunnel sections. This method can improve the overall longitudinal stiffness of the tunnel and reduce the deformation at the longitudinal circumferential joints. Although the longitudinal reinforcement rib has been applied in engineering practice, its reinforcement mechanism is not yet fully understood, and the reinforcement effect needs to be clarified.

There are few studies on the influence of staggered arrangement on the bearing characteristics of circumferential joints. What is the effect of misalignment on the mechanical properties of transverse connections? What is the mechanism of the influence of misalignment on the damage process and the phenomenon of the circumferential joint? There are no good answers to these questions, which need to be further explored. At the same time, when evaluating the safety of tunnel excavation and reinforcement, if the influence of misalignment is not considered, the bending resistance of the circumferential joint may be overestimated, resulting in the loss of the best reinforcement time or poor reinforcement effect. Therefore, to study the failure mode of circumferential joints in shield tunnels and the effectiveness of channel reinforcement, this study will analyze the failure process of circumferential joints in shield tunnels under shear load on the ABAQUS platform and study the influence of misalignment on the bearing capacity of circumferential joints, which is verified via model test.

#### 2. Model Building

#### 2.1. Geometric and Numerical Modeling

In this paper, the geometric model of the main structure is drawn using Revit (see Figure 3). Then, the model is imported into the numerical software ABAQUS 2020 for subsequent calculation. Along the longitudinal direction of the shield tunnel, the staggered assembly mode between the rings of the shield tunneling section is shown in Figure 2. The circumferential joints refer to the position where the two rings of the shield tunneling section are connected. The theme of this paper is the staggered deformation of the circular joints in the shield tunneling section. This paper aims to abstract and simplify the shear mechanical model of the circumferential joint in the physical model of the junction of the double-ring shield tunneling section. Therefore, in line with the principle of highlighting the structural characteristics that have a greater impact on the shear deformation of the joints and ignoring the structural characteristics with a smaller impact on the shear deformation of the joints, the following assumptions are made: assuming that the contact surface of the adjacent lining is a plane and ignoring the influence of the inter-segment water stop, sealing gasket, and concave-convex structure [22]. Through the calculation and analysis of the mechanical model, this study aims to understand the shear failure process of the circumferential joint of the shield tunneling section and the influence of channel steel reinforcement.

According to the actual situation of the shield tunnel spacing of a subway line in Fuzhou, the inner diameter of the shield tunnel is 2.75 m. Therefore, the circumference of the first ring shield tunneling section is 17.28 m. The segmental lining of each ring shield is connected to the adjacent ring through 16 longitudinal bending bolts in the longitudinal direction. Because the shear load acts along the normal direction of the outer ring of the shield tunneling section,

the bending radius of the shield tunneling section has no significant effect on the bearing capacity analysis and can be ignored. Therefore, the shield tunneling section model can be simplified. The circumferential joint can be simplified as the splicing of two rectangular concrete blocks. The dimensions of a single shield tunneling segment are  $0.60 \times 1.00 \times 0.35$  m, and the diameter of the bolt hole is 36 mm, as shown in Figure 4.



**Figure 3.** The staggered assembly pattern between the rings of shield tunneling segments: (**a**) two-ring shield tunneling segment assembly diagram; (**b**) schematic cross-section of shield tunneling segment.



**Figure 4.** Circumferential joints of shield tunneling segment model dimension drawing (Unit: mm): (a) front view of shield tunneling segment block; (b) side view of shield tunneling segment block; (c) top view of shield tunneling segment block; (d) shield tunneling segment splicing diagram.

The connector adopts an M30 double-head bending bolt. The actual half-ring shield segment lining width is 0.60 m. The cross-section of the shield segment lining is 1.00 m, which is divided into 16 equal parts along the ring line. The distance between each part is about 1.00 m. In terms of reinforcement measures, the longitudinal reinforcement rib consists of 14-channel steel with a length of 0.40 m, and its specific section size is shown in Figure 5. The reinforcement method involves welding perforated steel plates at both ends of the channel steel. The end of the bolt is then tightened with a nut to secure the reinforcing member. As shown in Figure 6, this establishes a strong connection between the reinforcing rib channel steel and the bending bolt.



Figure 5. Drawing of cross-section dimensions of channel steel (Unit: mm).



Figure 6. Localized Channel Reinforcement Diagram.

- 2.2. Model Parameterization
- Concrete constitutive model

The commonly used concrete structure models in ABAQUS include the plastic failure constitutive model, brittle cracking constitutive model, and diffusion cracking constitutive model. The brittle cracking constitutive model and the diffusion cracking constitutive model are suitable for analyzing the cracking behavior of concrete. The plastic failure constitutive model considers the elastic stiffness degradation caused by tensile and compressive deformation of concrete. The model is suitable for analyzing the stress and plastic failure of concrete under any type of load [20] and has good convergence. Because this paper aims to analyze the diffusion law of the concrete plastic zone around circumferential joints, a plastic failure structure is adopted in the lining concrete of the shield tunneling section. The specific parameters of concrete are shown in Table 1. In the definition of plastic damage intrinsic parameters, it is also necessary to define the compressive (see Figure 7)and tensile (see Figure 8) and properties of concrete, and some of the parameter values are given in the Bending bolt and reinforced channel steel constitutive in Table 2.

Parameter	Value	
Concrete strength class	C50	
Modulus of elasticity	34.5 GPa	
Poisson's ratio	0.167	
Κ	0.667	
Expansion angle	$30^{\circ}$	
Eccentricity	0.1	
$f_{b0}/f_{c0}$	1.16	
Viscosity parameters	0.0005	





Figure 7. Stress–strain diagram of concrete under compression.



Figure 8. Stress-strain diagram of concrete under tensile.

Stress/MPa	Inelastic Strain (Compression)	Damage Parameter	Stress/MPa	Inelastic Strain (Tensile)	Damage Parameter
24.3	0.00009	0.0576	2.73	0.00000	0.00000
28.5	0.00018	0.0944	2.42	0.00002	0.13940
33.1	0.00091	0.2831	2.02	0.00005	0.27222
30.3	0.00133	0.3690	1.70	0.00008	0.37648
28.5	0.00155	0.4104	1.45	0.00010	0.45651
24.8	0.00199	0.4849	1.26	0.00012	0.51870
23.1	0.00221	0.5176	1.12	0.00014	0.56801
20.1	0.00263	0.5742	1.01	0.00016	0.60792
18.8	0.00284	0.5986	0.91	0.00018	0.64082
15.6	0.00344	0.6591	0.84	0.00020	0.66838
13.2	0.00402	0.7049	0.78	0.00021	0.69180
12.0	0.00439	0.7296	0.57	0.00030	0.77057
10.0	0.00512	0.7688	0.46	0.00038	0.81575
9.2	0.00548	0.7846	0.39	0.00046	0.84522
8.0	0.00619	0.8106	0.34	0.00054	0.86604
7.0	0.00689	0.8311	0.31	0.00062	0.88159
5.6	0.00828	0.8612	0.28	0.00070	0.89368
3.0	0.01405	0.9213	0.25	0.00078	0.90336
2.4	0.01708	0.9359	0.24	0.00086	0.91131

Table 2. Partial parameter table of concrete tensile-compression characteristics.

The connectors between the segment joints are selected as M30 double-head arc bending bolts with a grade of 5.8. The bolt adopts a double folding line constitutive structure. The constitutive structure relationship is shown in Figure 9. OA represents the elastic section with a modulus of elasticity of  $E_S = 200$  GPa. AB represents the reinforced section with a modulus of elasticity taken as 0.01  $E_S = 200$  GPa. When the bolt reaches a yield strength of 400 MPa, the plastic strain is 0.002. When it reaches a tensile strength of 500 MPa, the plastic strain is 0.052. The channel steel used is Q235 steel, which has a modulus of elasticity of 200 GPa, yield strength of 235 MPa, and an ultimate strength of 375 MPa.



Figure 9. Bending bolt constitutive curve diagram.

Mesh Properties

For meshing, three-dimensional ten-node quadratic tetrahedral cells (C3D10) were selected for concrete and bent bolts, while three-dimensional four-node linear tetrahedral cells (C3D4) were used for channels.

#### 2.3. Contact Property Setting

Face-to-face contacts were chosen for the contact surfaces of the circumferential joints of the shield tunneling segment blocks and the contacts between the bolts and the inner walls of the bolt holes. In other words, the normal direction is set to have a hard contact, while the tangential direction uses a penalty function and defines the coefficient of friction. The values of the friction coefficient for different contacts are determined based on the material properties. The specific values of friction coefficients can be found in Table 3 [21].

Table 3. Friction coefficient of the contact surface.

Contact Surface	Segment and Segment	<b>Bolts and Segments</b>
Coefficient of friction	0.4	0.3

It is assumed that the nut of the bending bolt is always tightened, so the bending bolt and the hand hole portion of the shield tunneling segment block are subject to bound constraints.

#### 2.4. Boundary Conditions and Load Mode Selection

In the numerical calculations, the boundary conditions of the model are set, as shown in Figure 10. The left surface of shield tunneling segment 1 and the right surface of shield tunneling segment 2 are set with displacement constraint along the X-direction, that is, U1 = 0. The lower surface of shield tunneling segment 2 is set with the displacement constraint along the Z-direction, that is, U2 = 0, to secure the right side of the shield tunneling segment so that no displacement occurs during the loading of shield tunneling segment 1.



**Figure 10.** Load boundary diagram of the circumferential shear model (*Nj* is cylinder propulsion load, *F* is shear load).

For the circumferential joint shear mechanics model, the main focus of this paper is on the shear load and the cylinder thrust load it experiences during construction, as depicted in Figure 10. In Figure 10, the force along the positive direction of the *X*-axis represents the jack thrust load. The force along the negative direction of the *Z*-axis represents the shear load acting perpendicular to the outer surface of the shield tunneling segment. This force is applied linearly, starting from 0 during the specified period. The load activation sequence is to first apply the horizontal thrust and leave it unchanged, followed by the shear load. In this paper, we focus on analyzing the misalignment deformation pattern of the circumferential joint of a shield tunneling segment under shear load, as well as the shear damage of the circumferential joint in the case of reinforced and non-reinforced cases. To achieve this, we establish four cases, two for reinforced and two for unreinforced scenarios (refer to Table 4). Among them, Case 1-2 and Case 2-1 are designed to compare the difference in the amount of misalignment deformation of the circumferential joint under the same shear load, with and without channel reinforcement. This is conducted to illustrate the effect of channel reinforcement on the resistance of the circumferential joints to shear deformation.

Table	e 4.	Case	and	load	setting.
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Case	Step	Nj/MPa	F/MPa
Case 1-1	Unreinforced	1.4	0.5
Case 1-2	Unreinforced	1.4	0.8
Case 2-1	Channel steel reinforcement	1.4	0.8
Case 2-2	Case 2-2 Channel steel reinforcement		4.0

#### 3. Model Building

3.1. Simulation of Shear Failure in Segment Circumferential Joint

3.1.1. Segment Misalignment Deformation

The circumferential joint model of the segment is shown in Figure 11 and the calculated displacement maps of the shield tunneling segments for both cases are shown in Figure 12. From Figure 12, the maximum displacement of the left shield tunneling segment is 9.4 mm in Case 1-1 and 31.7 mm in Case 1-2.



Figure 11. Three-dimensional modeling load patterns.



Figure 12. Displacement cloud diagram: (a) Case 1-1 result; (b) Case 1-2 result.

The load–displacement curves of the two cases are shown in Figure 13. It can be seen from Figure 13 that the load–displacement curves in the two cases can be divided into three stages. In the first stage, the load increases sharply, and there is almost no misalignment in the shield tunneling section. This is mainly due to the friction between the circumferential connecting surfaces. The friction force and shear force offset each other in the vertical direction. In the second stage, the load remains relatively constant, but the deviation increases from 0 to about 6 mm. As shown in Figure 14, the main reason for the gap between the bolt hole and the bolt is that the segment will be subjected to the vibration load of the shield machine, the thrust load of the cylinder, the soil water outside the lining,

and the grouting pressure during the shield tunneling process. Manual tightening has a certain error, and the bolt will loosen. A certain gap between the bolt and the bolt hole will lead to circumferential dislocation. To simulate the actual situation, the gap is reserved for 6 mm in this paper. The reserved 6 mm gap is determined according to the full-scale test results. The load–displacement relationship of the third stage is nonlinear. This is mainly due to the shear load of the bending bolt at this stage. It can be seen from Figure 13 that in the initial stage of the shear failure of the circumferential joint, the misalignment only increases slightly with the increase in the load. This shows that the bending bolt, as the only connecting element at the circumferential connection, plays a role in resisting misalignment deformation. However, at the end of the third stage, the load–displacement curve becomes horizontal. This shows that under the same load increment, there is a clear misalignment at the circumferential joint.



Figure 13. Load-settlement curve (a): Case 1-1 result; (b) Case 1-2 result.



Figure 14. The gap between the bending bolt and the bolt hole.

As the misalignment deformation progresses, the bending bolt will contact the concrete on the inner wall of the bolt hole and be squeezed out. Because the stiffness of the bending bolt is greater than the stiffness of the concrete, the concrete around the bolt hole will undergo plastic deformation during the extrusion process.

Figure 15 shows the plastic deformation of concrete near the bolt hole in Case 1-1. It can be seen from Figure 15 that the concrete near the bolt hole has slight plastic deformation. Larger plastic deformation is concentrated in the upper part of the bolt hole. In Figure 15b, the plastic deformation is concentrated in the lower part of the bolt hole. This difference can be attributed to the misalignment of the circumferential joints during processing. The left side of the shield tunneling section is dislocated downward, while the right side is dislocated upward. Therefore, the plastic damage inside the shield tunneling section is mainly concentrated on the upper and lower surfaces of the bolt holes in each section. The main reason is that when the shield tunneling section is misaligned in the circumferential joint, the left side is misaligned downward, and the right side is misaligned upward. Therefore, the bent bolt is pressed on the upper and lower surfaces of the inner wall of the two bolt holes of the shield tunnel. This leads to plastic damage mainly concentrated in these two recombination regions. From Figure 15, the plastic deformation concentration of the upper and lower parts of the bolt hole in the shield tunnel section. In contrast, only

relative displacement occurred in the right segment. Therefore, the degree of extrusion of the concrete in the right section is strong, resulting in a large concentration of plastic deformation in the lower part of the right section.



**Figure 15.** Case 1-1 Plastic damage diagram of concrete at bolt hole (PE, Max. Principal. Average: 75%): (a) left segment injury; (b) right segment injury.

In Case 1-2, as the shear load increases, the concrete at the bolt holes of the shield tunneling segment experiences greater squeezing pressure. Consequently, more units around the bolt holes enter the yielding phase in both the left and right shield tunneling segments, as depicted in Figure 16.





#### 3.1.2. Segment Misalignment Deformation

The bent bolts act as connecting elements between the blocks of the shield tunneling segment and play a crucial role in resisting the misalignment of the circumferential joints. This is mainly because when two plastic hinges are formed on the bolt, the bolt loses the stiffness to resist the misalignment of the circumferential joints, and no new torque is generated on any part of the bolt. The circumferential joints lost their bearing capacity. The friction of high-strength bolts can first withstand the shear force. When the load increases to the point where the friction force is not enough to resist the shear force, the static friction force will be destroyed, resulting in a segmented misalignment. However, although the bolt is damaged at this point, the bolt rod is still in contact with the section and its elastic–plastic deformation can still be used to bear the shear force.

During the misalignment deformation of the shield tunneling segment, the central region of the bent bolt will first be compressed against the inner wall of the bolt hole, resulting in contact stress. The position of the contacts is illustrated in Figure 17.



Figure 17. Bending Bolt Contact Stress Location.

After the contact stress is generated, the left side of the bolt continues to experience vertical downward displacement as the amount of misalignment gradually increases. Under the combined action of these factors, the elements on the bent bolt gradually yield, forming a plastic hinge. When two plastic hinges are formed on the bolt, the load-carrying capacity of the circumferential joint is compromised [21].

In Case 1-1, the plastic hinge generated using the bending bolt is shown in Figure 18. It can be seen that there are two slight plastic yields on the surface of the bolt, which are mainly located on both sides of the bolt symmetry axis. The yield area is relatively small, and the plastic zone does not pass through the formation of plastic hinges. The bolt itself has almost no deformation, which indicates that the bolt also has shear bearing capacity.



Figure 18. Case 1-1 Distribution of the plastic zone of bending bolt (PE, Max. Principal. Average: 75%).

In Case 1-2, as the shear load increases to 0.8 MPa, the plastic yield zone and the deformation of the bending bolt also increase. It can be seen from Figure 19 that the area of the two plastic hinges is significantly larger than that of Case 1-1. They penetrate upward and downward, and the bolt itself has undergone significant deformation. This indicates that the bolt has completely lost its shear bearing capacity, and the structural integrity of the transverse connection has been destroyed.

PE, Max. Principal



Figure 19. Case 1-2 Distribution of plastic zone of bending bolt (PE, Max. Principal. Average: 75%).

# 4. Simulation of Shear Failure of Segment Girth after Local Channel Steel Reinforcement

# 4.1. Segment Misalignment Deformation

In Case 2, the focus is to study the correlation between misalignment deformation and shear load after the circumferential connection of the shield tunneling section is strengthened with channel steel. In addition, the analysis also includes a study of the types of damage that may occur to the circumferential connection bolts. Channel steel reinforcement is mainly used to fix the end of bending bolts and reinforced parts by tightening nuts. This ensures that the reinforced rib channel steel and the bending bolt are integrated and effectively resist misalignment and longitudinal tension. The specific reinforcement situation is shown in Figure 20. The shear loads of Case 2-1 and Case 2-2 are 0.8 MPa and 4.0 MPa, respectively, and the cylinder propulsion load is 1.4 MPa. The purpose of calculating Case 2-1 is to compare it with the unreinforced case, while Case 2-2 is to study the shear failure mode of the ring connection position after reinforcement.



Figure 20. Case 2 Channel steel reinforcement diagram.

Through calculation, we obtain the enhanced displacement cloud images in two cases, as shown in Figure 21. As can be seen from Figure 21, in Case 2-1, when the shear load is 0.8 MPa, the misalignment deformation of the left section is 7.7 mm. Compared with the 31.7 mm misalignment deformation under the same load without reinforcement, it is reduced by about 76%. These results show that the channel steel reinforcement structure has made a significant contribution to preventing the misalignment of the annular space. The mechanism of channel steel reinforcement is to tighten the end of the bolt and the reinforcing member through the nut so that the reinforcing rib and the bent bolt form a whole. These results show that the channel steel reinforcement structure has made a significant contribution to preventing the misalignment of the circumferential joint. When the load increases to 4.0 MPa, the section misalignment reaches 30.3 mm, and the channel steel reinforcement structure also shows noticeable deformation. Figure 22 shows the load-displacement curves of Cases 2-1 and 2-2. In Case 2-1, the deviation is 7.7 mm. In this case, the reinforced channel steel members are mainly used to resist shear loads. In Case 2-2, when the shear load reaches 2500 kPa, the main reason for the gradual increase in segmentation deviation is that although only one plastic hinge appears on the bending bolt at this time, and the bending bolt generally produces two plastic hinges before failure, the stress mode of the bolt after reinforcement with channel steel has changed, and the bolt itself has been deformed. The reinforced channel steel forms a bottom-up expansive plastic zone at the flange, so the bending bolt has been damaged at this time. As a result, the misalignment gradually increases.

The plastic yielding at the bolt holes of the concrete block in Case 2-1 is shown in Figure 23. Since the amount of misalignment is significantly reduced compared to the unreinforced condition, the extrusion load between the screw and the inner wall of the bolt hole is also relatively reduced, and the plastic zone is significantly reduced. In Case 2-2 (see Figure 24), the plastic zone in the bolt hole is significantly expanded compared to Case 2-1. This expansion is primarily caused by contact and compression between the bolt and the inner wall of the bolt hole.



Figure 21. The displacement cloud diagram: (a) Case 2-1 result; (b) Case 2-2 result.



Figure 22. Load–displacement curve: (a) Case 2-1; (b) Case 2-2.



**Figure 23.** Case 2-1 Plastic damage diagram of concrete at bolt hole (PE, Max. Principal. Average: 75%): (a) left segment injury; (b) right segment injury.



**Figure 24.** Case 2-2 Plastic damage diagram of concrete at bolt hole (PE, Max. Principal. Average: 75%): (a) left segment injury; (b) right segment injury.

#### 4.2. Bending Bolt Deformation

The bent bolts are connected to the two ends of the channel steel reinforcement member on the opposite connection block. This connection can lead to deviation. The stress of the bolt is not only from the extrusion of the bolt-hole wall but also from the tension of the channel steel. Due to the combined effect of these forces, the yield of the bending bolt will be different from that of the non-reinforced case. The details are shown in Figure 25. In the case of bending bolts, Case 2-1 deforms at the top and bottom and passes through the plastic zone. However, only slight deformation occurred in the bolt itself, and no evident deformation or yield occurred in the reinforced channel steel (see Figure 25). Therefore, the circumferential joint is not damaged.

PE, Max. Principal



Figure 25. Case 2-1 Plastic Zone Distribution of Bent Bolts (PE, Max. Principal. Average: 75%).

In Case 2-2, when the shear load increases to 4.0 MPa, as shown in the figure, the bending bolt deforms, and the original plastic zone expands. Although there is only one plastic hinge on the bending bolt at this time, and the general bending bolt will produce two plastic hinges before failure due to the change in the force of the bolt reinforced using the channel steel, the bolt itself has also deformed, and the reinforced channel steel also forms a bottom-up plastic zone on the flange (see Figure 26), so the bending bolt has been damaged at this time.

PE, Max. Principal



Figure 26. Case 2-2 Plastic Zone Distribution of Bent Bolts (PE, Max. Principal. Average: 75%).

#### 4.3. Stress Deformation of Channel Steel

After reinforcement with channel steel, the channel steel will also deform due to the increase in misalignment deformation, extrusion, and tensile force of the shield tunneling block. Figures 27 and 28 describe the stress and plastic deformation diagrams of the strengthened members in Case 2-1. The figure shows that when subjected to a shear load of 0.8 MPa, there will be evident stress concentration on the lower side of the channel steel flange. This stress concentration extends to the side of the web, but the stress values do not exceed the yield strength of the steel. On the contrary, as shown in Figures 29 and 30, local plastic yielding occurs at the connection between the channel web and the steel plate. When the load increases to 4.0 MPa, the whole channel steel appears to deform. Most of the regions on the flange and web enter the plastic yield state. The connection area between the channel web and the steel plate reaches the ultimate tensile strength of 370 MPa. This

shows that, at this point, the strengthening member itself, especially the plate and channel steel welding position, has experienced failure and destruction. The shear load of 4.0 MPa leads to damage to the circumferential joint of the bending bolt and the reinforced channel steel member. It can be concluded that the circumferential joint has lost its shear capacity and has been damaged.



Figure 27. Case 2-1 Reinforcement component stress cloud.



**Figure 28.** Case 2-1 Plastic deformation diagram of strengthened member (PE, Max. Principal. Average: 75%).



Figure 29. Case 2-2 Reinforcement component stress cloud (S, Mise. Average: 75%).



**Figure 30.** Case 2-2 Plastic deformation diagram of strengthened member (PE, Max. Principal Average: 75%).

#### 5. Full-Scale Tests

5.1. Experimental Study on the Shear Damage of Shield Segment Circumferential Joints and the Foot Size of Channel Reinforcement

The size of this test component is the same as that in Figure 4, and the customized wooden mold for this test is depicted in Figure 31. The handhole location is simulated using a wooden block cut to size, which can be easily removed after the maintenance of the member is completed. In this test, the clearance between the bending bolt and the inner wall of the bolt hole of the segment is 6 mm. The circumferential joint between the two segment blocks is simulated via two pieces of 1 mm-thick steel spacers, which can be removed from the side. This allows the spacer to be extracted when the concrete solidifies, forming the circumferential joint. At the same time, in anticipation of future lifting requirements, two lifting rings are preinstalled on the side of each of the two segment blocks to facilitate subsequent lifting operations.



Figure 31. Component formwork construction diagram.

To monitor the strain on the bending bolt, measure the stress value of the specific area, and determine whether the bending bolt has entered the yielding stage, it is necessary to install strain gauges on the bending bolt in advance. The test used the BFH120-3AA resistance strain gauges model. Fifteen measurement points were arranged for each bolt, and the specific distribution of measurement points is shown in Figure 32. Measurement points are primarily distributed along the bolt center axis on the left and right sides, as well as the lower side, with five measuring points arranged on each side. The figure



below shows the numbering of the measurement points. The unreinforced group is labeled A1–A15, and similarly, the reinforced group is labeled B1–B15.

**Figure 32.** Bent bolt measurement point layout. (**a**) Distribution of bolt measurement points; (**b**) position of the bolt measurement point around the segment block.

To determine the force condition of the channel steel, it is necessary to monitor the strain on the channel steel. The specific distribution of measurement points at the flange plate, web plate, and steel piece are shown in Figure 33. It mainly includes the distribution of five measurement points (F1–F5) in the web plate position, monitoring the tensile deformation of the middle and edge of the web plate; five measurement points (Y1–Y5 and Y6–Y10) at each side of the flange plate, and two measurement points (G1–G2 and G3–G4) at each side of the steel piece. These points are used to monitor the tensile deformation of the steel piece and the weld joint of the channel steel web plate. The tensile deformation of steel sheet and channel steel web welds is monitored.



Figure 33. Bent bolt measurement point layout.

An AD100 displacement sensor with a range of 100 mm is used to monitor the displacement of the block under shear load. Since the bottom of the circumferential joint and the base have been fixed with the ground anchor, it is only necessary to place the displacement sensor above the circumferential joint, as shown in Figure 34. The test simulates the whole process of misalignment failure of the circumferential joint of the shield segment under the action of smooth shear force under the condition of no reinforcement and channel steel reinforcement. The specific test device of the non-reinforcement group test is shown in Figure 35.

As shown in Figure 36, the loading device uses a jack, and a 1200-ton jack with sliding support is used in the vertical direction. The position of the sliding support ensures that the vertical axial pressure can be maintained in the middle even after the segment misalignment. The vertical load is transferred to the BWZ-1000 pressure sensor (measuring range of 1000 kN) through the jack and then evenly distributed to the member through the load-sharing steel plate. In the horizontal direction, two 200-ton jacks are fixed on the reaction wall, as shown in Figure 37. The horizontal load is transferred through two jacks

to a 30 mm-thick, 1120 mm  $\times$  600 mm solid component steel plate welded with two steel pads and then evenly transferred to the member.



Figure 34. Displacement point layout.



Figure 35. Loading process of segment shear test.



Figure 36. Vertical jacks and sliding bearings.



Figure 37. Horizontal jack.

As shown in Figure 38, the horizontal load value can be obtained by connecting the TS3860 static resistance strain gauge to the oil pump tank. It should be noted that the strain gauge must be calibrated in advance. The concrete base is anchored and fixed to the ground using anchor bolts. At the same time, to prevent the ring below the connection from tilting forward due to horizontal load, an L-shaped steel plate with stiffeners is installed between the left and right sides of the ring and the concrete base. There are holes connected to the anchor bolts on the steel plate. This measure can effectively ensure that the lower section and the concrete base remain stable when the upper section is misplaced. The loading sequence includes applying a fixed vertical jacking load to simulate the thrust of the shield machine's propulsion cylinder to the section and then gradually applying a horizontal jacking load until the circumferential connection structure is misaligned and loses shear resistance.



Figure 38. TS3860 static resistance strain gauge.

#### 5.2. Test Load Determination

In shield tunnel construction, the total thrust range of the propulsion cylinder of the shield machine is 8000–10,000 kN. The cylinder thrust per linear meter along the ring surface is 435–544 kN. Based on the actual working conditions of a subway line in Fuzhou City, the inner diameter of the shield tunnel is 2.75 m, resulting in a circumference of 17.28 m for a ring of tubes. Each ring of tubes is connected to the neighboring ring with 16 longitudinal bending bolts, with a spacing of 1.08 m between two longitudinal bolt holes. With the test component set at 1.0 m, the approximation is 490 kN. Each ring segment is equipped with 16 longitudinal bending bolts that are connected to the adjacent ring. The distance between two longitudinal bolt holes is 1.08 m. The length of the ring surface of this test component is 1.0 m, which allows for an approximation of the cylinder thrust force to be 490 kN. Considering the weight of the subloading steel plate and the pipe piece above the circumferential joint, the thrust force on the cylinder is discounted to a certain extent. Through calculation, the part's gravity is 5 kN. Therefore, the vertical jacking load should be 485 kN. When loading the vertical load, 485 kN is applied first, and it is kept unchanged. Horizontal loads are applied in increments of 10-20 kN until the circumferential joint structure is damaged. The criterion for assessing circumferential joint damage is based on the increase in horizontal load to a certain level and the continued

increase in misalignment between the two segments while it remains unchanged, indicating damage to the circumferential joint structure. The horizontal load is applied in increments of 10–20 kN until the circumferential connection structure is damaged. The criterion for evaluating the damage of the circumferential joint is that when the horizontal load increases to a certain extent, the misalignment between the two sections continues to increase and remains unchanged, indicating that the circumferential joint structure is damaged.

#### 5.3. Test Condition Setting

Two groups of tests were carried out in this study: one group was used to evaluate the shear failure at the circumferential joint without reinforcement, and the other group was used to evaluate the shear failure at the circumferential joint after reinforcement with channel steel. In both cases, a constant vertical load and a gradually increasing horizontal load are applied to simulate the failure development of the circumferentially connected structure. By comparing the two cases, we can determine the effectiveness of channel steel reinforcement in resisting the circumferential connection deformation caused by shear misalignment and bending bolt yield during the circumferential connection shear process. Figure 39 shows the loading condition without reinforcement. At this stage, no reinforcement measures are taken between the circumferential connections, and only the two ends of the bending bolt are tightened with the nut. At the same time, the adjacent parts of the circumferential connection are wrapped and fixed using four ribbed steel plates to prevent displacement when subjected to horizontal jacking loads.



Figure 39. Unreinforced condition loading diagram (strain gauge measurement).

Figures 40 and 41 describe the loading conditions in the unreinforced state. At this point, no reinforcement measures are taken between the circumferential joints, and only the end of the bending bolt is tightened with the nut. At the same time, the adjacent parts of the circumferential connection are wrapped and fixed using four ribbed steel plates to prevent displacement when subjected to horizontal jacking loads.



Figure 40. Reinforcement loading diagram.



Figure 41. Reinforcement channel diagram.

#### 5.4. Test Results and Analysis

5.4.1. Analysis of the Shear Process of the Circumferential Joint in Unreinforced Conditions

Figure 42 shows the misalignment of the circumferential joint position when subjected to destructive loads. It can be seen from the figure that there is a clear misalignment between the upper and lower steel tubes. Through measurement, it can be determined that the misalignment at the failure of the circumferential joint is 47.51 mm, and the corresponding shear load value is 933.33 kPa. As shown in Figure 43a, in the early stage of misalignment deformation, that is, when misalignment has not yet occurred, the concrete at the circumferential joint will crack and fall off slightly. With the increase in misalignment, cracks appeared at the longitudinal and vertical circumferential joints of the bolt holes at both ends. As shown in Figure 43b, there is an evident drop phenomenon at the circumferential joint. The main reason is that in the process of misalignment, the two ends of the bolt are fixed, and the misalignment of the concrete will make the bolt protrude from the concrete, resulting in the cracking of the joint position.



(a)

(b)

**Figure 42.** Deformation of segment misalignment in unreinforced conditions. (**a**) Upper and lower steel tubes; (**b**) Lower steel tubes.

Figure 44 depicts the shear load–misalignment curve for the unreinforced condition, which can be roughly divided into two stages for analysis. The initial stage involves increasing the shear load from 0 to 533.33 kPa in incremental steps. In this process, the misalignment between the segment blocks is 5.90 mm, which is relatively small. This indicates that the friction between the circumferential joint interfaces is resisting the shear load at this point. The second stage involves increasing the horizontal load from 533.33 kPa to 966.67 kPa. When the shear load is increased from 533.33 kPa, as indicated by the data measured using the displacement sensor, the upper segment block exhibits noticeable

misalignment deformation. As the jack thrust increases, the amount of misalignment also gradually increases. This specific trend is illustrated in Figure 44. At this point, the bending bolts and friction between the circumferential joint work together to resist the horizontal shear load. When the shear load reaches 966.67 kPa, the misalignment displacement between the segments is 47.51 mm. However, as the shear load continues to increase, the curve's curvature tends to become horizontal, and the amount of misalignment remains unchanged, the displacement of the segment increases sharply, indicating that the circumferential joint structure can no longer resist the shear load, and damage has occurred. When the horizontal shear load increment remains unchanged, the displacement of the segment increases sharply, indicating that the circumferential connection structure has been unable to resist the shear load, and damage has occurred.







Figure 44. Load-misalignment curve for unreinforced conditions.

The following conclusions can be drawn by comparing the results of load–misalignment under unreinforced conditions in Figures 13 and 44: (1) When the shear load is less than or equal to 600 kPa, under the same load, the error of the calculation results of the numerical

simulation and the full-scale test is between 13.3% and 28.7%, indicating a large error. However, when the shear load is greater than 600 kPa, the error of the dislocation is less than 10%. (2) The numerical simulation in this paper yields smaller values than the experimental results, which is mainly due to the cracking and falling of the concrete during the test. The damage of the concrete in the numerical results is relatively small.

#### 5.4.2. Analysis of the Shear Process of the Circumferential Joint under Reinforced Condition

Figure 45 shows the shear misalignment of the circumferential joint under the condition of channel steel reinforcement. It can be seen from the figure that there is an evident misalignment displacement between the two segments. The measurement results show that the misalignment at the damage of the circumferential joint is 53.87 mm, and the corresponding shear load is 2000 kPa.





As shown in Figure 46a, in the early stage of misalignment deformation, there were no noticeable cracks in the concrete at the circumferential joint and the bolt hole. With the increase in shear load, cracks appeared along the longitudinal direction around the bolt hole, and the phenomenon of falling blocks appeared at the circumferential connection, as shown in Figure 46b. The cracking mode in the reinforced state is different from that in the unreinforced state. This is mainly because the bolt and the channel steel stiffener form a shear unit. When concrete compresses channel steel webs, stress concentration will occur around the channel steel webs. In addition, the shear load in the reinforced state is greater than that in the unreinforced state. Figure 47 shows the shear load–displacement curve under the condition of channel steel reinforcement, which can be roughly divided into two stages for analysis. The initial stage is when the shear load gradually increases from 0 to 666.67 kPa. At this stage, the resistance to the shear force is mainly provided by the friction between the circumferential joints. The deviation between the circumferential joints is only 3.24 mm, indicating that the deviation deformation at this stage is very small. The second stage is the increase in shear force from 666.67 kPa to 2000 kPa.

Compared with the unreinforced case, the misalignment deformation of the reinforced section is significantly reduced by about 67% under the shear load of 933.33 kPa. This reduction is mainly attributed to the fact that the channel steel is welded to the steel plate and fixed at both ends of the bending bolt with a nut. This structure makes the reinforcing channel steel and the bending bolt form a shear unit. When the channel steel is sheared, the force on the web can be concentrated on the flange plate, achieving an effective shear effect.



**Figure 46.** Concrete cracking under reinforced conditions. (a) Cracking of concrete in the initial stage of misalignment deformation; (b) Cracking of concrete when the amount of misalignment increases.



Figure 47. Load-misalignment curve for reinforced conditions.

The load–misalignment under the reinforcement conditions in Figures 22 and 47 is similar to that of the unreinforced case. The amount of circumferential seam dislocation obtained through numerical calculation is smaller than that of the full-scale test, and the error is less than 20%.

## 5.5. Bent Bolt Strain Analysis

As the main connecting part of the circumferential joint, the bending bolt will produce a certain degree of deformation under the shear load. When the shear load does not increase or increases linearly, if the misalignment deformation continues to increase or expand, it can be inferred that the circumferential joint is damaged. This section will analyze the strain of the bending bolt after the failure of the circumferential joint in two cases.

#### 5.5.1. Strain Analysis of Bolts in Unreinforced Condition

As shown in Figures 48–52, the strain on the bending bolt is usually in the range of 700–1000  $\mu\epsilon$  after the circumferential connection is destroyed. In the initial stage of misalignment, the increase in strain is very small, which indicates that the force on the initial bolt is relatively small. It is worth noting that the strain values at positions A5

and A10–A12 eventually exceeded 2000  $\mu\epsilon$ , indicating that the bolts experienced the most significant deformation at these positions. The actual yield strain of the bending bolt is 2250  $\mu\epsilon$ , indicating that the bolt is closest to the yield strength at these positions and yields first. Under the same shear load, the numerical simulation results of bolt strain are 15.6–23.5% higher than the experimental results under the unreinforced condition.



Figure 48. Bolt strain curve for unreinforced conditions (A1-A3).



Figure 49. Bolt strain curve for unreinforced conditions (A4-A6).



Figure 50. Bolt strain curve for unreinforced conditions (A7–A9).



Figure 51. Bolt strain curve for unreinforced conditions (A10–A12).



Figure 52. Bolt strain curve for unreinforced conditions (A13–A15).

5.5.2. Strain Analysis of Bolts under Reinforced Conditions

Under the condition of reinforcement, the load–strain curve of the bolt is shown as follows. It can be seen from Figures 53–57 that most of the strain on the bending bolt is concentrated at about 1200  $\mu\epsilon$  after the circumferential joint is destroyed, which is generally larger than that of the unreinforced bolt. This is mainly due to the shear effect on the bolt caused by the misalignment of the circumferential joint and the tensile effect of the channel steel reinforcement structure. The strain of the bolt at positions B7–B9 exceeds 2000  $\mu\epsilon$ , indicating that the bolt experiences the maximum stress here and yields first. Under the same shear load, the numerical simulation results of bolt strain are 10.6–20.8% higher than the experimental results under the reinforced condition.



Figure 53. Bolt strain curve under reinforcement conditions (B1–B3).



Figure 54. Bolt strain curve under reinforcement conditions (B4-B6).



Figure 55. Bolt strain curve under reinforcement conditions (B7–B9).



Figure 56. Bolt strain curve under reinforcement conditions (B10–B12).



Figure 57. Bolt strain curve under reinforcement conditions (B13–B15).

# 6. Conclusions

In this paper, the finite element software ABAQUS is used to establish a threedimensional scale model of the ring joint of the curved bolt connection shield interval. The misalignment deformation of the interval block and the failure of the curved bolt under the action of lateral jacking force and different vertical shear loads are analyzed. After the local channel steel reinforcement, the misalignment deformation of the interval block, the deformation of the curved bolt, and the deformation of the channel steel under the force condition are analyzed. The main purpose of this chapter is to obtain the correlation between the shear load and the misalignment of the segmented block by applying the shear load to the segmented block. Then, the effect of channel steel reinforcement on restraining the misalignment of the segmented block and improving the shear capacity of the ring joint by applying local channel steel reinforcement at the ring joint position is examined. The numerical results are compared with the results of the pedal test. The main conclusions are as follows:

- (1) Under the condition of no reinforcement, the shear failure process of the circumferential joint can be divided into three stages. In the first stage, the vertical load increases, but the misalignment between the shield tunneling sections is almost entirely due to the friction between the contact surfaces of the circumferential joints. In the second stage, the load hardly increased, but the misalignment increased by about 6 mm, which was mainly due to the gap of  $\Delta = 6$  mm between the outer surface of the bending bolt and the inner wall of the bolt hole. In the third stage, the load–displacement relationship is nonlinear, which indicates that the bending bolt is subjected to shear action. As the misalignment develops, the concrete around the bolt hole will also appear to have evident plastic expansion.
- (2) After strengthening the circumferential joint position of the shield tunneling section with channel steel, the misalignment of the circumferential joint is significantly reduced. Compared with the misalignment of the unreinforced state under the same load (about 76%), this reduction shows that the channel steel reinforcement structure plays a significant role in preventing the misalignment of the circumferential joint. Under the same shear load, the misalignment amount in the reinforced state is significantly less than that in the unreinforced state, reducing the extrusion load between the bending bolt and the inner wall of the bolt hole and reducing the plastic zone of the concrete around the bolt hole.
- (3) In the unreinforced condition, when the shear load reaches the destructive load of the circumferential joint, there will be two noticeable plastic areas on the surface of the bending bolt, which is equivalent to the formation of two plastic hinges. At this point, the bolt also undergoes large deformation, losing its shear capacity completely and causing the circumferential joint to be destroyed. In the reinforced condition, the bending bolt is connected to the grooved steel through the steel plate and nut to form a system. In this scenario, the bending bolt will only produce one plastic hinge in the circumferential joint when losing its shear capacity, while the shear load also affects the reinforcing rib of the grooved steel. At the same time that the shear load is applied, it is also enforced by the channel steel reinforcing ribs. The shear capacity is lost in the circumferential joints, and the bent bolts produce only plastic hinges.
- (4) Channel steel, as a reinforcing system at the circumferential joint, also caused significant deformation during circumferential joint damage. Most of the areas on its flange and web enter a plastic yield state. However, according to the results of numerical calculations, the main reason for the destruction of the channel steel reinforcing ribs is the tensile ultimate strength of the steel in the connecting area between the channel steel web and the steel piece. This means that the reinforcing member itself is damaged at the position where the steel sheet is welded to the channel steel, and the reinforcing member fails.
- (5) In this paper, the numerical calculation results of the shear load–misalignment relationship and bending bolt yield are consistent with the full-scale test results. The

misalignment of the circumferential joint obtained through numerical calculation is smaller than that of the scale test. The main reason is that the concrete cracks and falls during the test, and the numerical results have relatively minor damage to the concrete. The yield position of the bending bolt is also basically consistent with the test results, and the bolt strain obtained via the test will be relatively small.

Author Contributions: Conceptualization, H.S. and L.Z.; methodology, H.S.; software, H.S. and L.Z.; validation, H.S. and L.Z.; formal analysis, H.S. and L.Z.; investigation, T.D., Z.Y. and J.Q.; resources, T.D., Z.Y. and J.Q.; data curation, Z.Y. and J.Q.; writing—original draft preparation, H.S.; writing—review and editing, H.S., L.Z., T.D., Z.Y. and J.Q.; visualization, H.S., L.Z., T.D. and J.Q.; supervision, T.D., Z.Y. and J.Q.; project administration, L.Z., T.D., Z.Y. and J.Q.; funding acquisition, L.Z. All authors have read and agreed to the published version of the manuscript.

**Funding:** This research was funded by National Natural Science Foundation of China grant number [41977233, 42272338].

Data Availability Statement: Data are contained within the article.

**Conflicts of Interest:** Author Zengquan Yang was employed by the company Fuzhou Metro Line 6 East Diversion Section Corporation Limited. Author Jianpeng Qin was employed by the company China Construction Infrastructure Corporation Limited. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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