Research on mechanical behavior of circular concrete-filled steel tube arch joints with built-in opening stiffener

GONG Sai¹, CHENG Gao²
1 Nanyang Institute of Technology Henan Province Nan yang 473004 China
2 Chang’ an University Highway school Shaanxi Province Xi’an 710064 China
Corresponding author’s e-mail: lioavse@163.com

Abstract: For the concrete-filled steel tubular tension nodes, the opening stiffener can effectively reduce the stress concentration of the joints and increase the ultimate bearing capacity and tensile stiffness of the joints. For the concrete-filled steel tubular arch ribs, the steel arches are subjected to both horizontal and normal forces. Open type stiffener has an important influence on the mechanical performance of the arch rib joint, and the mechanism of the joint force transmission is more complicated. Taking a bearing circular concrete-filled steel tube arch bridge as an example, a nonlinear finite element model is established by selecting arch rib joints to analyze the influence of the setting of Open type stiffeners on the mechanical properties of CFST arch joints. The results show that after the Open type stiffener is set, the failure mode of the joint is represented by the buckling deformation of the arched steel tube and the obvious deformation of the arch rib steel pipe. The Open type stiffener avoids the void of the joint steel pipe and concrete, ensuring the steel pipe and concrete at the arch rib joint. The built-in opening stiffener is an effective form of improvement for concrete-filled steel tubular arch rib joints.

1. Preface
The steel pipe is filled with concrete to form a combined structure, which can enhance the buckling resistance of the steel pipe, improve the compressive strength of the core concrete, and has the advantages of high axial bearing capacity and good ductility, and is widely used as a stress-based structure, such as shaft of steel tube concrete ribs, concrete-filled steel trusses, etc [1]. However, due to the external load, concrete shrinkage and creep, and the like, the bonding force between the steel pipe and the concrete is easily overcome and the relative slip, that is, the debonding occurs. When the concrete tube cross-section void rate is 1%, the ultimate bearing capacity of the axial column is reduced by 20% [2]. For the concrete-filled steel tubular arch rib joints, the horizontal force parallel to the arch axis and the normal force perpendicular to the arch axis will be generated by the axial force of the upper column of the arch. The horizontal force is first assumed by the steel pipe, and then the bonding force of the steel pipe and concrete will be partially The horizontal force is transmitted to the concrete inside the pipe [3]. Since the bonding force between the steel pipe and the concrete is very limited, it is easy to produce the slippage and debonding of the steel pipe and the concrete interface at the joint, which seriously reduces the ultimate bearing capacity of the concrete filled steel arch rib. PBL stiffened CFST is a new type of structural structure recently proposed [4]. After the perforated steel plate is welded to the inner wall of the steel pipe and filled with concrete, the PBL shear joint can be fully utilized to strengthen the bond between the steel pipe and the concrete interface force. For the concrete-filled steel tubular tension nodes, the PBL stiffeners can effectively reduce the stress
concentration of the joints and increase the ultimate bearing capacity and tensile stiffness of the joints \[5\]. For the compression joints of CFST arch ribs, the steel arch is affected by both horizontal and normal forces. PBL stiffeners have an important influence on the mechanical behavior of the arch rib joints. The mechanism of joint force transmission is more complicated. To this end, the paper takes a bearing circular concrete-filled steel tube arch bridge as an example, selects the arch rib joint to establish a nonlinear finite element model, analyzes the influence of the setting of PBL stiffeners on the mechanical properties of CFST arch rib joints, and further improves the steel pipe.

2. Selection of parameters of concrete-filled steel tubular arch ribs

The typical force diagram of the arch rib joint of the upper concrete-filled steel tube arch bridge is shown in Fig. 1. It can be seen from Fig. 1 that the angle between the concrete-filled steel tubular arch rib and the arch upper column is \(\theta\), the arch rib is subjected to the axial pressure \(N\), and the arch upper column is subjected to the axial force \(P\); the boundary condition of the arch rib can be simplified to one end of the arch rib segment. For the fixation, one end can only slide freely along the axis of the arch rib.

![Figure 1. Schematic diagram of node stress](image)

In order to analyze the influence of PBL stiffeners on the mechanical properties of concrete-filled steel tubular arch rib joints, a set of arch-ribbed joints were designed by taking a steel-reinforced concrete arch bridge \[6\] as an example. The structural form and dimensions of the test pieces are shown in the figure. The selected arch rib and the arch upper column is 45. The length of the arch rib section is 5.00 m, the height of the arch upper column is 2.23 m, and the pressure of the arch rib axis is 4000 kN. The arch rib is a circular steel tube concrete, and the upper column of the arch is a rectangular hollow steel pipe, and the steel pipe of the arch rib and the arch upper column is equal to 16 mm. Since the width-to-thickness ratio of steel pipe is an important index affecting the mechanical properties of concrete-filled steel tubular structures \[7\], the thickness of steel pipes is 8mm for comparative analysis. The steel grade used for steel pipes is Q345, and the concrete filled in the pipe is C50 concrete. The opening aperture and spacing of the PBL stiffeners are set according to the structural requirements in \[8\].

![Figure 2. Node construction form](image)

(a) Common node construction (b) Set the PBL stiffener node configuration

Figure 2. Node construction form

3. Establishment of concrete-filled steel tubular arch rib joint model

The concrete-filled steel tubular arch rib joint model considers material nonlinearity, geometric nonlinearity and nonlinearity of steel-mixed interface contact. The constitutive model of steel adopts the ideal elastoplastic constitutive relation. The yield strength \(\sigma_y\) of Q345 steel is 345 MPa, the elastic
modulus $E_s$ is $2.06 \times 10^5$ MPa, and the Poisson's ratio $\nu_s$ is 0.3$^{[9]}$. The constitutive model of concrete adopts the concrete plastic damage model provided by ABAQUS finite element software. The stress-strain relationship of concrete is calculated according to the constitutive relationship of concrete in the Code for Concrete Structure Design (GB50010-2010)$^{[10]}$. The axial compression strength of C50 concrete is $37.36$ MPa, the elastic model $E_c$ is $3.45 \times 10^4$ MPa, and the Poisson's ratio $\nu_s$ is 0.167. The steel-concrete interface contact model consists of the normal contact and the tangential contact of the interface. The normal contact adopts “hard contact”, and only the normal pressure can be transmitted between the interfaces; the tangential contact adopts the classic “Coulomb friction” model. The concrete with higher rigidity is used as the main surface, and the steel pipe is used as the secondary surface, and the friction coefficient is 0.3.

The steel tube unit adopts S4R four-node reduced integral shell unit, the concrete adopts C3D8R eight-node reduced integral hexahedral unit, and the PBL stiffener uses S4R four-node reduced integral shell unit. The PBL stiffener uses the "pseudo-rebar" method, which is implemented in the ABAQUS by the command "embedded element technique". The meshing results of the node model are shown in Figure 3.

Table 1. Node boundary conditions

| Reference point | DX | DY | DZ | RX | RY | RZ |
|-----------------|----|----|----|----|----|----|
| A               | 1  | 1  | 1  | 1  | 1  | 1  |
| B               | 1  | 1  | 0  | 1  | 1  | 1  |
| C               | 0  | 0  | -  | 0  | 0  | 1  |

4. Finite element analysis

4.1 Destruction form

Through the displacement loading of the arch upper column, it is found that whether the Open type stiffener is set under the bearing capacity limit working state has different influence on the failure mode of the arch rib joint. The arch rib steel pipe at the intersection of the arch rib joints without PBL stiffeners is bent outward on the side and top faces, and the steel pipe and the concrete interface are hollowed out, and the steel pipe on the arched column is subjected to compression buckling deformation. There is no obvious deformation of the ribbed steel pipe at the intersection of the arch rib
joints with Open type stiffeners. There is no void at the interface between the steel pipe and the concrete, and the steel pipe on the arched column is subjected to buckling deformation. From the point of view of the failure mode of the node, after the PBL stiffener is set, the resistance of the ribbed steel pipe at the joint is obviously enhanced, and the joint between the steel pipe and the concrete is reliable, which can effectively avoid local deformation of the steel pipe and voiding of the interface between steel and concrete.

4.2 Stress distribution
In order to analyze the influence of PBL stiffeners on the stress distribution of concrete-filled steel tubular arch rib joints, the principal stress distribution of the arch rib joints is given when the axial pressure of the arch on the arch reaches 10000kN or 0.6 times, as shown in Fig. 6. It can be seen from Fig. 6 that the region where the node Mises stress is greater than 345 MPa, that is, the yield region appears red in the figure. After the PBL is set in the arch rib joint, the yielding area of the steel pipe at the joint is significantly reduced. This is mainly because the PBL stiffener is used to ensure that the steel pipe and the concrete are co-stressed at the arch rib joint, and the horizontal force of the arch upper column is effectively transmitted to the concrete inside the pipe.

4.3 Ultimate bearing capacity analysis
In order to analyze the influence of opening stiffeners on the ultimate bearing capacity of concrete-filled steel tubular arch rib joints, Fig. 7 shows the axial load and displacement curves of the upper arch. It can be seen from Fig. 7 that the ultimate bearing capacity of the opening stiffeners is equal under the ultimate bearing capacity state. The reason is that the node failure under the ultimate bearing capacity is dominated by the buckling failure of the arched steel tube and the ultimate bearing capacity of the joint. It is equal to the axial bearing ultimate bearing capacity of the steel pipe on the arch; in normal use, the bearing capacity of the node is increased by more than 50% after the opening stiffener is set. Taking the ratio of the slope of the axial load to the displacement as the joint stiffness,
the stiffness of the joint can be increased by about 47% after setting the opening stiffener. It can be seen that the bearing capacity and joint stiffness of the CFST compression joints are significantly enhanced after the PBL stiffeners are set.

Figure 7. Load-displacement curve of the arch on the arch

5. Conclusion
(1) The failure mode of the concrete-filled steel tubular arch rib under extreme working conditions is that the arch rib steel pipe at the junction of the joints is bent outward on the side and top direction, the steel pipe and the concrete interface are debonded, and the steel pipe on the arch is pressed. After the Open type stiffener is set, the failure mode of the joint is represented by the buckling deformation of the arched steel tube and the arch rib steel tube has no obvious deformation.

(2) Open type stiffener can significantly increase the bonding force between steel tube and concrete, and solve the problem of interface debonding in arch rib joint area; under the action of arch upper column load, PBL stiffener is set to avoid the void of joint steel pipe and concrete, which guarantees the steel pipe at the rib joint is co-stressed with the concrete.

(3) Under normal use conditions, the ultimate bearing capacity and joint stiffness of the CFST compression arch joints are significantly enhanced after the PBL stiffeners are set. The engineering example in the paper shows that the bearing capacity of the node is increased by more than 50% and the node stiffness is increased by about 47% after the Open type stiffener is set. It can be seen that setting the Open type stiffener is a beneficial attempt to improve the concrete-filled steel tubular arch rib joint.

About the Author:
Gong Sai, female, 1986-, Tieling, Liaoning Province, lecturer, graduated from Chang'an University in 2012 with a master's degree in architecture and civil engineering. Since 2013, he has worked at Nanyang Institute of Technology.
E-mail: lioavse@163.com, Tel:18837718366
Address: No. 80, Changjiang Road, Wancheng District, Nanyang City, Henan Province

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