The Analysis of Interface Normal Stress of Short Column of Square Concrete-Filled Steel Tube with Axial Compression

Zhengqi Zhang¹, Yongjian Liu¹,³, Zhiheng Zhang¹ and Gao Cheng¹,³

1. School of Highway, Chang’an University, Xi’an, Shaanxi Province, China.
2. Shaanxi Provincial Major Laboratory for Highway Bridge & Tunnel, Xi’an, Shaanxi Province, China.
3. Key Laboratory of Bridge Detection Reinforcement Technology Ministry of Communications, Xi’an, Shaanxi Province, China.

Abstract. The interface normal stress reflects the interaction between the steel tube and the concrete in the tube, which is helpful to distinguish the time and size that begin to appear confinement effect of the concrete filled steel tube. The typical CFST members in engineering applications may be loaded such as loading through the whole cross section, loading through steel alone and loading through concrete alone, etc. Establishing nonlinear finite element model to analyse the interface normal stress between steel and concrete along the section width, short column height and with the change of axial compressive load, the results show that the different loading mode of CFST column interface normal stress along the width of the cross section showed a "trough" distribution, but the value is different, sorted by size in descending order is loading through concrete alone, loading through the whole cross section, loading through concrete alone. When steel tube and concrete are subjected to loads, the effective length of steel tube confined concrete is about 0.55 times the width of the section, and the normal stress of the interface is almost 0 in the unconstrained area after 0.5 times of the ultimate load.

Keywords: concrete-filled steel tube; square; interfacial normal stress; confinement effect; finite element analysis.

1. Introduction

The square concrete-filled steel tube (CFST), with its advantages of high bearing capacity, simple joint structure and convenient construction is suitable to be used as the main axial compressive bridge components such as bridge piers, arch ribs and truss chord, and is more widely used in bridge engineering [1]. Under the influence of the construction phase, construction precision and material time variation concrete-filled steel tube maybe in the state other than simultaneous stress of concrete-filled steel tube and concrete. For example, Large section size of Concrete filled steel tube bridge pier, the load is usually applied to the concrete in the pipe, which belongs to the stress mode of concrete only. Due to the negative influence of shrinkage and creep of concrete and casting quality, the concrete inside the pipe may get empty and even lead to the stress only on the steel pipe [2]. The influence of the change of load mode on the axial stiffness and bearing capacity of concrete filled steel tubes cannot be ignored [3-4]. Mechanical properties of concrete-filled steel tube and concrete interface affect the working mechanism of concrete-filled steel tube columns, joints, beams, etc. which has been a research hotspot of concrete-filled steel tube structures [5]. The interface mechanical behavior of concrete-filled steel tube can be divided into tangential bonding-sliding and normal bonding-separation, and the interface tangential behavior affects the bearing capacity, stiffness, transmission length of concrete-filled steel.
tube joints and so on [6]. The interface normal behaviour affects the hoop effect, ductility and bearing capacity of concrete-filled steel tubular column. On the basis of a large number of tests of tangential bond slippage on the interface of concrete-filled square steel tube, the generation mechanism of interfacial bond strength and the influence law of parameters have been given, forming the constitutive relation of tangential bond-slip [7-9]. There are few studies on the normal mechanical behavior of interface. Chen Bao Chun [10] and some other scholars obtained the standard values of the normal bond strength of the square concrete-filled steel tube by using pulling and bending methods respectively, and pointed out that the influence of concrete strength on the normal bond strength is not obvious, while the surface condition of concrete and steel tube has a great influence on the normal bond strength. The normal stress of the interface reflects the interaction between the steel tube and the concrete inside the tube, which is helpful to identify the time and size of the hoop action. With the limitations of testing methods and techniques, it is not possible to directly measure the interface normal mechanical characteristics of short concrete-filled steel tubular column during the axial compression. Therefore, the paper is proposed to analyze the interface normal stress of the concrete-filled steel tubular column under different stress mode by the method of numerical simulation, reveal the combined action of concrete-filled steel tubular column, and provide theoretical support for the optimization design of concrete-filled steel tubular axial compression elements.

2. Design of Short Column Parameters of Square Concrete-Filled Steel Tube

The load-bearing model reflects all possible stress state of concrete-filled square steel tube in engineering. The interface normal stress of short column of concrete-filled square steel tube varies significantly with the change of load-bearing model. The relative width-to-thickness ratio is one of the most important parameters which influences interfacial design of concrete-filled steel tube construction. According to the specifications, in order to prevent local buckling in the elastic stage of steel, the thickness is set to be 4 millimeters in the paper. The larger the hoop coefficient is, the stronger the capacity of the steel tube confined concrete is. In this paper, the hoop coefficient is relatively large. The interface normal stress is relatively high to compare and analyze the changes caused by the load-bearing model. Based on the analysis above, the structural dimension and material property of the short column are shown in Table 1. The structural dimensions and material values of CFST-01 and CFST-02 are the same in Table 1. CFST-03 carries out concrete hollowing treatment within 20 millimeters of the top surface of components so that the load is applied only to the steel section and its other structures and material values are the same as those of CFST-01 and CFST-02. The steel pipe is Q345 and the concrete in the pipe is C30. The loading mode of each specimen is shown in Figure 1.

| Number   | Force exerting modes                  | a×a×t (mm) | H/mm | fck/MPa | fy/MPa |
|----------|--------------------------------------|------------|------|---------|--------|
| CFST-01  | loading through the whole cross section | 100×100×4  | 300  | 20.1    | 345    |
| CFST-02  | loading through concrete alone        |            |      |         |        |
| CFST-03  | loading through steel alone           |            |      |         |        |

Note: CFST - * middle FT is Square Concrete Filled Steel Tube Column, * represents specimen number; a is width and length of Square Steel Tube, t is wall thickness of steel tube, H is the length of concrete filled steel tubular column, fck is the axial compressive strength of concrete and fy is yield strength of steel.
3. Establishment of Nonlinear Finite Element Model

The establishment of finite element model takes material nonlinearity, geometrical nonlinearity and contact nonlinearity into consideration.

(1) Constitutive relation of steel and concrete

The stress-strain relationship of steel is set to be elastic-plastic curve of a bifold line. The elastic modulus of steel at elastic stage is set to be $E_s$ ($2.06 \times 10^5\text{MPa}$) and Poisson’s ratio is set to be $\nu_s$ (0.283). The elastic modulus of steel at plastic stage is set to be 0.01 $E_s$ and Poisson's ratio is set to be $\nu_s$ (0.2). According to the formulas in national standard code for design of concrete structures (GB 50010-2010) [12]. We can get the values of axial compressive strength and elastic modulus of concrete. The constitutive relation of concrete adopts concrete plastic damage model in ABAQUS finite element software [13]. The concrete uniaxial compression, uniaxial tension model adopts the stress-strain relationship in national standard code for design of concrete structures (GB 50010-2010) [12]. The concrete compression damage and tensile damage model adopts damage factor-strain relationship of concrete in national standard code for design of concrete structures (GB 50010-2010) [12].

(2) Cell type selection and model grid partitioning

Based on ABAQUS finite element software, steel tube uses S4 four-node fully integrated shell element, concrete uses C3D8 eight-node linear hexahedral element simulation, and loading plate uses rigid body element simulation. The model grid is divided by sweeping method with minimum grid transition, and the square concrete-filled steel tube model network is divided as shown in Figure 2.

Figure 1. Force exerting modes.

Figure 2. Mesh partition.
(3) Steel-concrete interface contact relations, model boundary and load conditions
The steel-concrete interface contact model is composed of normal contact and tangential bond slip. In view of the stiffness, we regard concrete as the main surface, steel pipe as the secondary surface. The normal contact between steel tube and concrete is based on the viscous damage model in ABAQUUS finite element software. The normal and tangential sliding behaviors of the contact interface are derived from the viscous sliding constitutive relations measured by the square concrete-filled steel tube interface push-out test. In other words, relative slip of the interface occurs only when the interface stress $\tau_e$ and the stress remains as $\tau_e$, the slip does not happen before it. The critical stress value and shear modulus of the interface of the concrete-filled square tubular are evaluated according to the constitutive relation of the interface of the concrete-filled square tubular in reference [9].

The reference point RP is set in the loading plate centroid. The reference point is coupled with the loading plate to constrain translational degrees of freedom in the X, Y and Z directions of the reference point RP1 and to constrain translational degrees of freedom in the X, Y directions of the reference point RP2. Applying 10mm displacement in the Z-positive direction of the reference point RP2, and the position of the reference point is shown in Figure 2c. By changing the contact between the loading plate corresponding to the reference point RP2 and the square concrete-filled steel tube column section to realize different loading models.

4. Result Analysis
The paper extracts the interface normal stress along the height direction of the short column, along the width direction of the section and its variation with the load, so as to fully grasp the interface normal stress of the CFST. According to the symmetry of the square section, only one of the steel tube panels is subjected to stress analysis. According to the interface normal stress in the post-treatment of ABAQUUS, the compressive stress is positive and the tensile stress is negative.

(1) Normal stress distribution along the column height
Based on the analysis above, the normal stress of the interface along the column height is selected at the corner of the section and the midpoint of the side as shown in Figures 3 and 4. The normal stress at the corner of the square section and the midpoint of the edge can reflect the variation range of stress. From Figures 3 and 4, we can know that the normal stress at the interface presents significant non-uniformity along the height of the short column, the normal stress at the end of the short column changes violently, and the normal stress at the middle of the short column is relatively uniform. We can also know that the normal stress at the corner interface of different load-bearing modes is mainly compressive stress, but the stress values are quite different. But stress values from small to large in order for model C (force only on the steel tube), model A (force on the steel tube and concrete simultaneously, model B (force only on the concrete).

![Figure 3. Normal stress distribution at the corner.](image-url)
Based on the above analysis, the normal stress of H/2 section interface at the ultimate load is the most representative to recognize the hoop action of the short column of CFST, as shown in Figure 5. As seen in Figure 5, interfacial normal stress under different loading mode all presents the “groove shape” distribution, but the numerical values are quite different. From small to large in order, it is the stress only on steel tube like model C, common on steel tube and concrete like model A, and only on concrete like model B. The normal stress on the steel tube at the interface is close to 0. When both steel tube and concrete bear force together and only concrete bear force, the normal stress of interface presents as compressive stress, with the largest corner and the smallest midpoint.

The greater the normal stress of the interface, the stronger the effect of the steel tube on the concrete of the tube. When only the concrete is stressed, the full section of the steel pipe constrains the concrete inside the tube. When the steel tube and the concrete are jointly stressed, the effective length of the confined concrete of the steel tube is about 0.55 times the width of the section, and the interface normal stress of the unconstrained area is almost 0.

(2) Normal stress distribution along the length of section

In order to analyze the moment when the action of the concrete-filled steel tubular hoop occurs, the variation of the interface normal stress of the H/2 section with the loading history is shown in Figure 6. It can be seen from Figure 6a that the interface normal stress presents a “changing-increasing-decreasing” trend with the increase of the load under the common stress mode. The interface normal stress remains the same and is almost close to 0 before reaching the ultimate load of 0.5 times, indicating that the hoop effect of steel tube and concrete has not yet played. As the load reaches the ultimate load of 0.9 times.
the steel tube has the strongest restraining effect on the concrete inside the tube when the interface normal stress reaches the maximum value. As the load continues to increase, the interface normal stress decreases. It can be seen from Figure 6b that only the concrete stress mode is significantly different from the common stress mode of steel tube and concrete, and the interface normal stress tends to increases with the increase of the load and then tends to be unchanged, and the restraining effect of the steel tube on the concrete inside the tube is accompanied by the load. It can be seen from Figure 6c that under the stress mode of the steel tube, the interface normal stress is mainly tensile stress, and the stress increases with the increase of the load. But it is much less than the normal bond strength of the concrete filled steel tube of 0.86 MPa [10], indicating that the steel pipe and concrete interface remain fully bonded.

**Figure 6.** The variation curve of interfacial normal stress with axial load.

5. Conclusion
The paper analyzes the variation of the normal stress along the section width, column height and axial pressure of the composite column interface by using numerical simulation method to analyze the steel tube and the concrete are jointly stressed, only the concrete is stressed and only the steel tube is stressed, and reveals the size and timing of the concrete-filled steel tubular shaft clamp.

1) The interface normal stress of concrete-filled steel tubular columns has a “groove” distribution along the section width under different loading modes, but the numeric value is different. It’s changes from small to large order is only the steel tube is stressed, the steel tube and the concrete are jointly stressed and only the concrete is stressed.

2) When the steel tube and the concrete are jointly stressed and only the concrete is stressed, the interface normal stress is expressed as compressive stress, and the square section has the largest stress at the corner and the minimum stress at the midpoint. When only the concrete is stressed, the full section of the steel pipe constrained the concrete inside the pipe. When the steel tube and the concrete are jointly
stressed, the effective length of the confined concrete of the steel tube is about 0.55 times the width of 
the section, and the interface normal stress of the unconstrained area is almost 0. When only the steel 
tube is stressed, the interface normal stress is tensile stress.

3) When the steel tube and the concrete are jointly stressed, the combined effect of steel tube and 
concrete before reaching the ultimate load of 0.5 times has not yet been exerted. As the load increases, 
the interface normal compressive stress gradually increases. When the ultimate load of 0.9 times is 
reached, the steel tube has the strongest restraining effect on the concrete inside the tube. When concrete 
only under stress mode, the restraining effect of steel tube on the concrete inside the tube is accompanied 
by the occurrence of load. In the stress mode of steel tube only, the interface normal stress is mainly 
tensile stress, but the stress value is small, and the steel pipe and concrete interface can still maintain 
fully bonded state.

Reference

[1] ZHOU Xuhong, LIU Yongjian, JIANG Lei, et al. The research summary on behavior of PBL 
stiffened concrete-filled rectangular steel tubu [J]. China Journal of Highway and Transport, 2017, 
30 (11): 45-62.

[2] TU Yaguang, YAN Donghuang, SHAO Xudong. Influence of debonding on ultimate bearing 
capacity of concrete filled steel tube arch bridge with single circular tube [J]. Journal of Harbin 
Institute of Technology, 2010, (12): 1999-2002.

[3] GUO Lanhui, ZHANG Sumei, LIU Jiepeng. Experimental study on mechanical properties of 
Concrete-filled Square Steel Tubes under different loading modes [Z]. Chengdu: China Steel 
Construction Society Association for Steel-Concrete Composite Structures, 2005, 05 (37): 145-148, 
156.

[4] GUO Lanhui, ZHANG Sumei, LIU Jiepeng. Experimental research and theoretical analysis on the 
mechanical properties of Concrete-filled Square Steel Tubes under different loading modes[J]. 
Engineering Mechanics. 2008, 25 (9): 143-148.

[5] LIU Yongjian, LI Hui, ZHANG Ning. Effect of interface state on flexural performance of 
rectangular concrete-filled steel tubular members. [J]. Journal of Architecture and Civil 
Engineering, 2016, (01): 15-21.

[6] Liu J, Zhou X, Gan D. Effect of friction on axially loaded stub circular tubed columns [J]. Advances 
in Structural Engineering, 2016, 19(3): 546-559.

[7] LIU Yong-jian, CHI Jian-jun. Push-out Test on shear bond strength of CFST [J]. Industrial 
Architecture, 2006, (04): 78-80.

[8] LIU Yong-jian, LIU Jun-ping, CHI Jian-jun. Test on shear bond behaviors at interface of CFST [J]. 
Journal of Guangxi University (NATIONAL SCIENCE EDITION), 2010, (01): 17-23.

[9] LIU Yong-jian, LIU Jun-ping, GOU yong-ping, et al. Bond-slip mechanics behaviors of structures 
CFST[J]. Chang’an University (NATIONAL SCIENCE EDITION), 2007, (02): 53-57.

[10] LIU Zhenyu, CHEN Baoshun. Experimental study on normal bonding strength of concrete filled 
steel tube interface [J]. Journal of Guangxi University (NATIONAL SCIENCE EDITION), 2012, 
(04): 698-705.

[11] People’s Republic of China. National standard code for design of steel structures [S]. Beijing, 2003.

[12] People’s Republic of China. National standard code for design of concrete structures (GB 50010-
2010) [S]. Beijing, Ministry of Housing and Urban-Rural Construction of the People’s Republic of 
China, 2010.

[13] CHENG Gao. Research on the Mechanism of Rectangular Concrete-filled Steel Tube Structure 
Stiffened with PBL [D]. Xi’an: Chang’an University, 2015.