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Experimental research on ultimate bearing capacity of N-joints of grouted square steel tube trusses

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Abstract: Cave-in failure is apt to occur in joints of trusses made of square hollow sections. In order to turn the failure mode into a strength failure mode of joint members, the idea is proposed that the chord of the truss is grouted to increase the cave-in bearing capacity of a hollow tube chord. An experiment of eight specimens of N-joints made of grout-filled square steel tubes is performed. Based on the experimental study, the geometrical parameters of specimens are analyzed, and the effects of the confinement index ξ, the spacing between the two web members g and the ratio of side length of the vertical web member to that of the chord β on the behavior of specimens are investigated through simulation analysis by an ANSYS program. Based on the test results and simulation analyses, the mechanical properties and the failure modes of this kind of joints are analyzed and the formulae to predict the ultimate bearing capacities corresponding to different failure modes are developed. The ultimate bearing capacity of compressive N-joints is calculated in accordance with the cave-in failure mode of a chord member; the ultimate bearing capacity of tension N-joints is calculated in accordance with the punching-shear failure mode; the ultimate bearing capacity of a chord member is calculated in accordance with the shear failure mode in normal sections.

Key words: N-joint; truss made of grout-filled square steel tube; ultimate cave-in bearing capacity; simulation analysis

In recent years, outer-jacketing structures used to add stories to existing buildings have increasingly drawn more attention, and reinforced concrete high-rise mega frame structures are used more widely as well[1-2]. Enlightened by the reconstruction (extension) project of Suifenhe Qingyun Market, a design idea, "self-supporting concrete floor during construction", is proposed[1], and composite prestressed concrete beams, in which a grouted square tube truss is encased, are used as the main beams of floor systems to support the deadweights of the concrete floors and the construction loads during concreting. N-joints are the main forms of chord joints in a grouted square steel tube truss[3]. Test studies on eight specimens of N-joints are carried out to support the research on the composite pre-stressed concrete beams. The mechanical behaviors and the failure modes are analyzed and formulae to calculate the ultimate bearing capacity of the joints corresponding to different failure modes are proposed.

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1 General Introduction of the Test

1.1 Design of specimens

The grouted-square-tube N-joints (see Fig. 1) are designed to make the vertical web member compressional and the inclined web member tensile. The chord and the vertical web member are grouted to prevent the chord from cave-in failure and the vertical web member from compression failure. The characteristic parameters of eight specimens to be tested are summarized in Tab. 1.

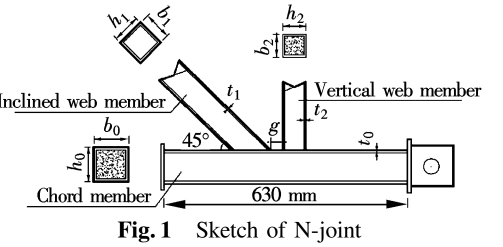


Fig. 1 Sketch of N-joint

1.2 Mechanical properties of materials

The specimens are made from square steel tube of Q235 or Q345 grade and their mechanical properties are listed in Tab. 2.

The grout inside the tubes is made from ordinary Portland cement of P. O42.5 grade, UEA bulking agent, and FDN superplasticizer. The mixture ratio of the grout is shown in Tab. 3. The average of the axial compression strength and the elastic modulus of the hardened grout are $\mu_{fc} = 28.1\ \text{N/mm}^2$ and $E_c = 1.8 \times 10^4\ \text{N/mm}^2$, respectively.

Tab. 1 Summary of characteristic parameters of specimens

Number	Chord $b_0 \times h_0 \times t_0$/ (mm·mm·mm)	Inclined web member $b_1 \times h_1 \times t_1$/(mm·mm·mm)	Vertical web member $b_2 \times h_2 \times t_2$/(mm·mm·mm)	β_1	β_2	g/mm	N_c/kN
CRN1	80 × 80 × 2.75	50 × 50 × 5	50 × 50 × 5	0.625	0.625	30	50
CRN2	80 × 80 × 2.75	60 × 60 × 6.25	50 × 50 × 5	0.750	0.625	30	50
CRN3	80 × 80 × 2.75	70 × 70 × 5	50 × 50 × 5	0.875	0.625	30	50
CRN4	80 × 80 × 2.75	70 × 70 × 5	30 × 30 × 2.75	0.875	0.375	25	50
CRN5	80 × 80 × 2.75	70 × 70 × 5	40 × 40 × 2.75	0.875	0.5	25	50
CRN6	80 × 80 × 2.75	70 × 70 × 5	50 × 50 × 5	0.875	0.625	25	50
CRN7	80 × 80 × 4	70 × 70 × 5	40 × 40 × 2.75	0.875	0.5	25	50
CRN8	80 × 80 × 5	70 × 70 × 5	40 × 40 × 2.75	0.875	0.5	25	50

Notes: β_1 is the ratio of the side length between the inclined web member and the chord member; β_2 is the ratio of the side length between the vertical web member and the chord member; g is the interspacing between the two web members; N_c is the axial compression force applied on the chord member.

Tab. 2 Mechanical properties of steel tube

Size	Steel grade	Member	f_y / MPa	f_u / MPa	E_s / GPa	ν
80 × 2.75	Q235	Chord	264.5	319	0.186	0.28
30 × 2.75	Q235	Web	250.6	310	0.200	0.28
40 × 2.75	Q235	Web	274.3	304	0.200	0.26
50 × 5	Q345	Web	441	499	0.201	0.27
60 × 6.25	Q345	Web	314	385	0.196	0.28
70 × 5	Q345	Web	449	497	0.198	0.26

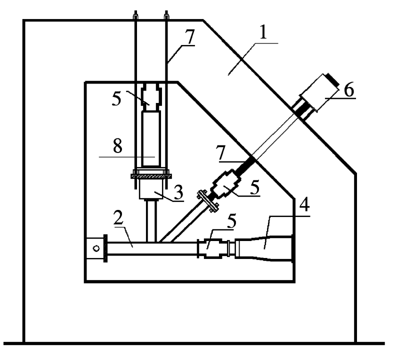
Tab. 3 Mixture ratio of grout material

Water cement ratio	Percentage accounting for weight of cement/%	
	UEA bulking agent	FDN superplasticizer
0.4	7	0.7

1.3 Loading and testing

1.3.1 Loading device and mechanism

The test is performed in a reinforced concrete ring beam as shown in Fig. 2. First, the ultimate bearing capacity of the specimen to be tested is predicted[4-5], and the specimen is preloaded to calibrate the data acquisition device before testing. When the test begins, some loads are applied on the chord to fix it by manual jack, followed by monotonic, stepped and active compression force on the vertical web member and tension force on the inclined web member by two jacks, respectively. The ratio of the tension force on the inclined web member to the compression force on the vertical web member is maintained as 1.414 by accurate control of a hydraulic pump to keep the joint vertically in balance. Each loading step applied on the tensile web member or the compressive web member is 10% of the predicted ultimate load simultaneously up to 60% of predicted ultimate loads. When reaching 60% of the predicted ultimate loads, the loading step become 5% of the predicted ultimate loads till the loads do not increase any more.



1—Ring beam for loading; 2—Specimen of N-shape joint; 3—Hydraulic pressure jack; 4—Manual jack; 5—Sonsors; 6—Hydraulic pressure jack; 7—Steel tension rod; 8—Steel pier

Fig. 2 Loading device

1.3.2 Testing scheme

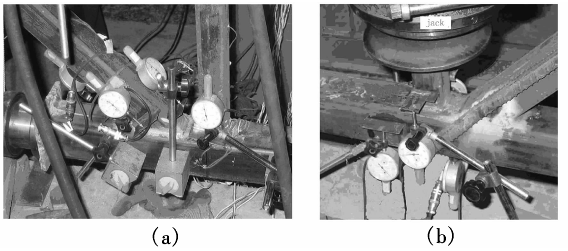
The following two aspects are considered in the testing scheme:

1) Measurement of axial forces of members

The axial forces are applied on the chord; the vertical and inclined web members are measured by oil pressure gauges and transducers, respectively.

2) Measurement of deformation of chord tube wall

Different testing schemes are adopted for different failure modes. For specimens CRN1 to CRN3, punching-shear failure will occur, the uplift deformation of the top flange of the chord at the intersection of the inclined web member with the chord is measured by dial gauges set as shown in Fig. 3(a). For specimens CRN4 to CRN8, cave-in failure will occur, the cave-in deformation at the top flange of the chord is measured by dial indicators installed as shown in Fig. 3(b).



(a) (b)

Fig. 3 Photos of deformation testing. (a) Uplift deformation; (b) Cave-in deformation

2 Failure Modes and Phenomena

Of the test specimens, three failed in the punching-shear failure mode of the chord tube and the others in the cave-in failure mode of the top flange of the chord.

2.1 Punching-shear failure of chord

In this test study, specimens CRN1 to CRN3 failed in the punching-shear failure mode of the chord (see Fig. 4). The top surface of the chord is ripped along the intersection of the inclined web member with the chord. The axial tension force on the inclined web member versus the uplift deformation of the top surface of the chord wall in the direction of the inclined web member axis and β_1 is shown in Fig. 5 based on the test results of the three specimens. It can be seen from Fig. 5 that the larger the side-length ratio β_1, the smaller the uplift deformation and the more suddenly the failure occurs. The uplift deformation of the top surface of the chord is generally not large when the joint fails in the punching-shear failure mode of the chord and this mode of failure is known to be brittle.


(a) (b) (c)

Fig. 4 Photos of the punching-shear failure mode of chord. (a) CRN1; (b) CRN2; (c) CRN3

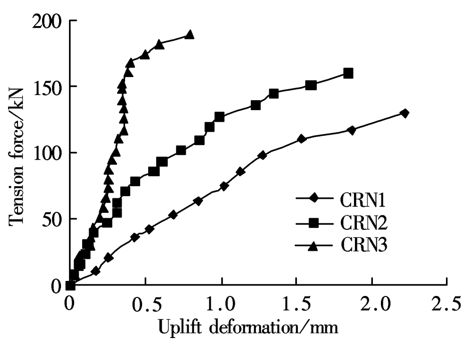


Fig. 5 Axial tension force on the inclined web member vs. the uplift deformation of chord

2.2 Cave-in failure of chord

The specimens CRN4 to CRN8 are strengthened by welding reinforcing steel bars to prevent the chords from punching-shear failure. As a result, the chords of these specimens fail in the cave-in failure mode as shown in Fig. 6. Remarkable cave-in deformation at the intersection of the compression member with the chord in the top surface of the chord occurs and the side surface of the chord swells out. The loads versus the cave-in deformations of the chords and β_2 are shown in Fig. 7. From Fig. 7 it can be seen that the notable elastic-plastic deformation of the joints occurs when they fail, and the mode of failure is ductile. The compression forces on the vertical web members corresponding to 3% of the cave-in deformations of the chords are regarded as the ultimate cave-in bearing capacities of the specimens of the joints.

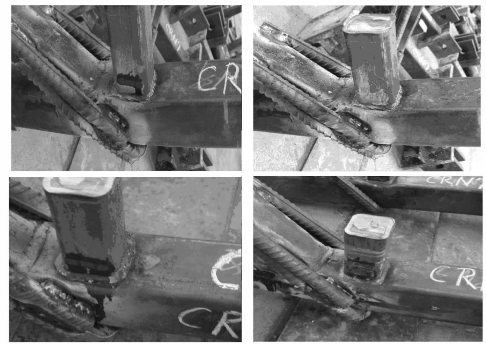


Fig. 6 Photos of the cave-in failure mode of chord

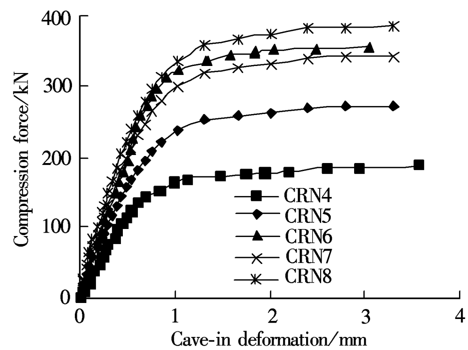


Fig. 7 Compression force vs. cave-in deformation

3 Calculation Formulae of Ultimate Bearing Capacity of Joints

3.1 Punching-shear failure mode of chord

Punching-shear failure is caused by shear failure of the chord tube wall and occurs at the parts of intersection of the inclined web member with the chord.

Finite element (FE) simulation analysis of the tested N-joints is performed by ANSYS software[6], and the results show that the failure location at the upper wall of the chord tube differs with the different spacings between the two web members, g. When g satisfies

$$g \leqslant 1.5(1-\beta)h_0 \tag{1}$$

the punching-shear failure location is demonstrated in Fig. 8(a). When Eq. (1) fails, the failure locations are shown in Fig. 8(b). The parameter b_{ep}, shown in Fig. 8, is a function of the width-depth ratio of the chord tube wall and is determined by test results [7]. Through regression analysis of the results from the test and finite element analysis, the calculation formula of b_{ep} can be obtained:

$$b_{ep} = \frac{14}{b_0/t_0} b_2 \tag{2}$$

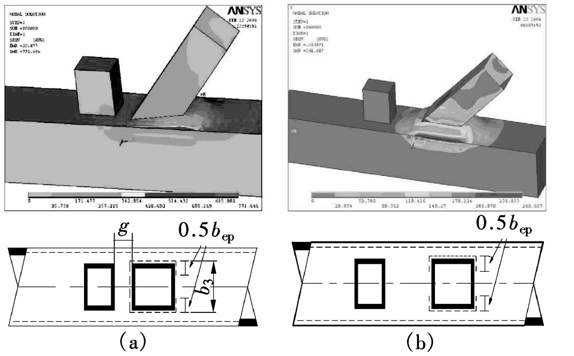


Fig. 8 Stress distribution of finite element models under failure load and location of punching-shear failure on the top flange of chord (shown by broken line). (a) Eq. (1) fails; (b) Eq. (1) is true

Punching-shear failure is caused by the vertical component of the tension force applied on the inclined web member, $N_1 \sin\theta_1$. The punching-shear load-bearing capacity of the joint is equal to the effective punching-shear area times the shear strength of the tube wall of the chord, and can be calculated as

$$N_1 = \frac{f_y t_0}{\sqrt{3}} \left(\frac{2h_1}{\sin\theta_1} + b_{ep} + b_1 \right) \frac{1}{\sin\theta_1} \tag{3}$$

Comparisons of the punching-shear bearing capacities of specimens CRN1 to CRN3 between the results of Eq. (3) and those from the test are listed in Tab. 4. It shows that the calculated results are in good agreement with the test data.

Tab. 4 Comparison of punching-shear bearing capacities between the results of Eq. (3) and those from test

Specimens	Test results P_u^t/kN	Calculated results P_u^c/kN	$\frac{P_u^t - P_u^c}{P_u^t}$ / %
CRN1	130.1	128.1	−1.5
CRN2	160.1	153.7	−3.9
CRN3	189.9	179.3	−5.5

3.2 Cave-in failure mode of chord

The formula of the ultimate cave-in bearing capacity is developed based on the test results of 15 T-joints[8] and 5 N-joints. It is considered that the ultimate cave-in bearing capacity N_u is mainly provided by the local compression bearing capacity of the hardened grout, and the grout is strengthened by the tightening restraint effect of the chord tube that made the grout in a three-dimensional compression state. The formula may be established by regarding the local compression load-bearing capacity of the hardened grout, N_{cu}, as the basic item and by taking the influence of the tightening restraint of the steel tube into account, and is expressed as

$$N_{cu} \leqslant 0.9 \beta_c \beta_l f_c A_l \qquad \beta_l = \sqrt{\frac{A_b}{A_l}} \tag{4}$$

where the local compression area A_l is the intersect area of the compression web member with the chord tube wall; the calculated bottom area A_b is determined on the principle that the local compression area is concentric and symmetric with the calculated bottom area; and the other parameters are in accord with *Code for Design of Concrete Structures* (GB 50010—2002).

Based on the test results, the magnitude of the tightening restrain effect may be determined by two parameters: the confinement index ξ and the ratio of the side length of the vertical web member to the chord β. The enhancement of local compression bearing capacity is considered in this paper through multiplying N_{cu} by factor k which is expressed as

$$k = 2.755\sqrt{\xi} - 1.156\beta^2 - 0.209 \tag{5}$$

where $\xi = \frac{f_y A_s}{f_{ck} A_c}$; A_s is the cross-section area of chord tube; A_c is the section area of hardened grout in the chord.

Finally, the equation to calculate the ultimate cave-in bearing capacities of joint chords is presented as

$$N_u = k N_{cu} \tag{6}$$

where N_u is the local compressive load-bearing capacity of the grouted-square-chord joint; N_{cu} is the local compressive load-bearing capacity of the hardened grout in the tube of the chord; k is the enhancement factor for the compressive strength of the hardened grout by the tightening-ring restraint of the tube.

Comparisons of the calculated results by Eq. (6) with test data are listed in Tab. 5. The calculated results are in a good agreement with test results.

Tab. 5 Comparison of results by Eq. (6) with test results

Specimens	Test results P_u^t/kN	Calculated results P_u^c/kN	$\frac{P_u^t - P_u^c}{P_u^t}$ / %
CRN4	185.1	182.4	−1.5
CRN5	271.2	268.7	−0.9
CRN6	354.6	353.8	−0.2
CRN7	343.1	338.1	−1.5
CRN8	385.3	387.4	0.5

3.3 Shear failure mode of normal section of chord of N-shape joint

The design of N-joints may be controlled by this failure mode[5], which occurs on the chord between the two web members.

The assumption is made that the shear force on the cross-section of the chord can be undertaken by the side wall of the chord and the hardened grout in the tube. As a result, the shear-bearing capacity of the normal section is calculated by

$$V_u = A_c f_{cv} + A_{sw} f_{sv} \tag{7}$$

where A_c is the intersection area of the hardened grout in steel tube; A_{sw} is the web area of steel tube; f_{cv} is the shear strength of the hardened grout, $f_{cv} = 0.2 f_c$; f_{sv} is the shear strength of the chord steel tube.

4 Conclusions

1) The test of eight specimens of N-joints of grouted-square-tube trusses is performed and valuable test results are accumulated.

2) Three kinds of failure modes of N-joints and corresponding calculation methods of the ultimate bearing capacity are presented.

3) The formulae to predict the ultimate bearing capacities of N-joints corresponding to different failure modes are proposed, which can serve as references in engineering design.

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弦杆灌浆方钢管桁架 N 型节点极限承载力试验研究

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摘要:空钢管桁架 N 型节点易发生压陷破坏,为了使杆件破坏先于节点破坏而发生,提出了在弦杆内灌浆以提高节点压陷承载力的设想. 进行了 8 个灌浆方钢管桁架 N 型节点的承载力试验. 基于试验结果,进行了试件的几何参数分析,研究了套箍系数、支杆间隙和支主杆边长比等参数对节点性能的影响. 基于试验结果和模拟分析结果,揭示了这类节点的受力机理与破坏模式,提出了对应于不同破坏模式的节点承载力计算公式:N 型受压节点及受拉节点承载力分别按弦杆压陷破坏和冲剪破坏模式进行计算;弦杆的承载力要按弦杆直剪破坏模式进行校核.

关键词:N 型节点;灌浆方钢管桁架;压陷承载力;模拟分析

中图分类号:TU393.3;TU317.1