Research Article

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Experimental study on square hollow stainless steel tube trusses with three joint types and different brace widths under vertical loads

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Abstract: This article reports the experimental behavior of square hollow stainless steel tubular trusses under static loading. A total of five specimens, including three trusses with K-joint, one truss with N-joint, and one truss with T-joint, were tested to study the effect of different outer widths of brace members and the types of joint on the flexural performance of square hollow stainless steel tubular trusses. The failure modes, flexural rigidity, load carrying capacity, ductility, load versus displacement curves, and load versus strain curves of all the tested specimens are presented. It can be seen that the chords of all specimens experienced surface plasticity. The test results indicate that the specimen with T-joint has the best ductility. The flexural rigidity of the truss with the K-joint is better than that of specimens with N-joint or T-joint. The flexural rigidity of trusses with the K-joint was found to increase with the increase of outer width (D) of the brace members varying from 38 to 80 mm. Besides, the load-carrying capacity per unit weight of the specimen with T-joint is better than that of specimens with N-joint or K-joint.

Keywords: tubular truss, failure modes, flexural rigidity, ultimate load carrying capacity, ductility, overall deflection

1 Introduction

Steel tubular truss structure is one of the main forms of spatial structures. Due to its advantages of lightweight, high strength, and beautiful shape, it has been widely used in large-span and super-large-span structures such as stadiums, exhibition halls, and airport terminals in recent years. Sun [1] carried out the finite element analysis on the initial stress, wind load, and other factors of the space tubular truss used in the stockyard enclosure project of Yonggang, determining that cables should not be used in this structure.

In the hollow section structure, one or more tube (branch tube) with a small diameter is usually welded to the surface of the tube (main tube) with large diameter, so as to form intersecting joints, which has the advantages of simple structure, material saving, and strong bearing capacity. According to the connection mode between the main tube and the branch tube, the steel tube joints can be divided into two main forms: intersecting joints and tube plate joints. The section of the steel tube is closed and has equal radial strength with good compressive resistance, bending resistance, and torsion resistance. In a steel tubular truss, the brace mainly bears the action of tension bending or compression bending load, and the chord mainly bears the axial force. The steel tubular truss structure can be divided into plane tubular truss and space tubular truss. Space tubular truss has been widely used in industrial buildings such as long-span trestle support. The spatial tubular trusses used in long-span trestle supports are generally rectangular in section, which have greater lateral stiffness and better overall stability compared with the inverted triangle space steel tubular trusses commonly used in civil buildings.

Currently, abundant research results have been obtained on steel tubular truss at home and abroad. Shasha et al. [2] established the full-scale finite element model of the tubular truss in titled belly pole using MSC Marc software and carried out static load tests. The results showed that the joint

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strength could meet the requirements of the overall bearing capacity of the structure, but the stress concentration in the joint area was obvious. Ma et al. [3] studied the flexural performance of tubular trusses with the rectangular section theoretically and proposed a new calculation model for flexural stiffness, which assumed that the truss chords and braces were connected by springs. Yiqun et al. [4] carried out the finite element analysis on the long-span rectangular section multiplanar tubular truss to simplify the calculation method of global stability bearing capacity, indicating that the top chord of the structure could be regarded as a laced axial compression member. Shi et al. [5] studied the failure mechanism of rectangular section tubular truss arches. The variable section spatial inverted triangle steel tubular truss proposed by Jinghai et al. [6] has been proved by eight calculation models to reduce the steel consumption by about 16%. Chen et al. [7] studied the out-of-plane stability of 16 different large-span spatial tubular trusses during hoisting. According to the description of Ling et al. [8], most of these studies used numerical simulation to study the mechanical properties of steel tubular trusses in practical engineering applications, which provides mature research methods for the following experimental analysis.

The joint strength and seismic resistance are the important factors that restrict the development of steel tube structures. The joint of steel tube intersecting is usually the weak part of the structure due to the obvious stress concentration. Qingxiong et al. [9] carried out fatigue tests on CHS tubular joints and analyzed fine cracks with nondestructive testing equipment. The results showed that the fatigue crack initiation occurred at the crown point near the main tube side, which had the maximum hot spot stress. The fatigue failure of the joints was brittle failure within the elastic range. Suo et al. [10] obtained the cumulative evolution law of joint welding materials through cyclic load experiments. The cyclic hardening phenomenon of the joint welding materials was observed with the increase in the number of cycles. Cui et al. [11] conducted cyclic load tests on steel tube joints and used three types of methods to evaluate their fatigue performance and proposed the hysteresis model. EZ et al. [12] carried out the finite element analysis on 81 spatial KT joints under bending load. Azari-Dodaran and Ahmadi [13] simulated and studied the axial compression performance of 54 spatial steel tube KT joints in fire. Pandey et al. [14] conducted a numerical study on the compression resistance of cold-formed full chord supported joints of S900 and S960 steels. Based on the study by Bayock et al. [15], the study of fatigue performance, welding strength, fire resistance, and hysteresis of steel tube joints provides a reference for the analysis of the local failure mechanism of tubular trusses in this article.

To meet the service requirements, it is usually necessary to strengthen the steel tube intersecting joints. Many scholars have also studied various reinforcement methods. Xie et al. [16] found that the ultimate bearing capacity significantly increased by filling concrete in chords of tubular joints. Ronghua et al. [17] found that compared with ordinary joints, the stiffened diameter joints had better energy dissipation performance. The stainless steel tubular truss perfectly unifies the two important structural properties of strength and durability. Fan et al. [18] carried out fire tests on six stainless steel SHS tubular joints. On the basis of the existing design criteria, Feng et al. [19] put forward the ultimate stress prediction formula of the stainless-steel hybrid tubular joint. Up to now, the research on the design method and mechanical properties of stainless steel tubular truss is less, and it is a subject with important research significance. This article mainly studies the flexural performance of stainless steel truss. The failure mode, bearing capacity, global deflection, and load-strain curve of each specimen are investigated.

2 Experimental study

2.1 Test specimens

The stainless steel tubular trusses with square hollow sections were tested under static loading. A total of five specimens were fabricated varying the type of joint (K-joint, T-joint, and N-joint) and the outer width of the brace (38.0, 60.0, and 80.0 mm) to study the mechanical performance of square hollow stainless steel tubular trusses. All specimens are labeled according to the material, type of joint studied by Abadi [20], and the outer width of brace investigated by Dutta et al. [21]. As a result, the specimens can be expediently distinguished.

In this article, a total of five square stainless steel tubular trusses, named ST-K-B38, ST-K-B60, ST-K-B80, ST-N-B80, and ST-T-B80, were built by reference to the CIDECT code [22]. The variables explored in the test program include the outer width of the brace and the type of joint. Besides, “K” means the truss with a K-joint, “T” denotes that the vertical brace and the top chord form a T-joint, “N” implies that the vertical brace and the diagonal brace form an N-joint, as shown in Figure 1(a), (d) and (e). Besides, the variable “38,” “60,” and “80” denotes the outer width of the corresponding brace of 38.0, 60.0, and 80.0 mm, respectively. The geometry, boundary conditions, and loading application of five square hollow stainless steel tubular

trusses are exactly symmetrical. Therefore, it can be concluded that the arrangement of axial strain is also in symmetry along the truss span.

Table 1 gives a minute presentation of the dimension arrangement of all truss specimens. Figure 1 is the three-dimensional diagram of the five trusses. Dimensions of the specimens are as follows:

- The nominal dimensions of the top chord of tested specimens are identical. More concretely, the overall length, width, and height are 3,300, 100, and 100 mm, respectively.
- The nominal dimensions of the bottom chord members of specimens “ST-K-B38,” “ST-K-B60,” and “ST-K-B80” are also identical, in which the aforementioned three parameters are 3,000, 100, and 100 mm, respectively.
- The overall length, width, and height of the bottom chord members of specimens “ST-N-B80” and “ST-T-B80” are 2,500, 100, and 100 mm, respectively.
- For all the specimens, the effective span between the two end supports of the top chord is 3,000 mm.

(a)

(b)

(c)

(d)

(e)

Figure 1: Schematic sketch of square hollow stainless steel tubular trusses: (a) specimen ST-K-B80, (b) specimen ST-K-B38, (c) specimen ST-K-B60, (d) specimen ST-N-B80, (e) specimen ST-T-B80.

Table 1: Details of all specimens

Specimens	Type of joints	Components	D (mm)	t (mm)	D/t	E (MPa)
ST-K-B38	K-joint	Top chord	100	2	50	203,001
		Bottom chord	100	2	50	203,001
		Brace	38	2	19	203,001
ST-K-B60	K-joint	Top chord	100	2	50	203,020
		Bottom chord	100	2	50	203,020
		Brace	60	2	30	203,020
ST-K-B80	K-joint	Top chord	100	2	50	202,960
		Bottom chord	100	2	50	202,960
		Brace	80	2	40	202,960
ST-N-B80	N-joint	Top chord	100	2	50	202,990
		Bottom chord	100	2	50	202,990
		Brace	80	2	40	202,990
ST-T-B80	T-joint	Top chord	100	2	50	203,070
		Bottom chord	100	2	50	203,070
		Brace	80	2	40	203,070

- The effective span of specimens “ST-K-B38,” “ST-K-B60,” “ST-K-B80,” “ST-N-B80,” and “ST-T-B80” between the end supports of the bottom chord are 2,500, 2,500, 2,500, 2,000, and 2,000 mm, respectively.
- Besides, the distance between two adjacent tubular joints is 500 mm along the truss span. The wall thickness (t_0) of all trusses is 2.0 mm.

The weld connections of chord and brace members were built based on the American Welding Society (AWS D1.1/1.1M) Specifications [23], using gas tungsten arc welding. Mao *et al.* [24] conducted the welding performance investigation to artificially optimize the argon arc welding parameters and obtained the most appropriate dimension that can allow the maximum tensile strength of the welding joint to reach more than 90% of the base metal. Therefore, the plasticity of stainless steel after yield can be fully developed. The minimum weld size should be assigned to a larger value from 3.0 mm and $1.5t$, where “ t ” is the smaller thickness of the chord and brace at the stainless steel tube joint. The A102 type elongation and tensile strength of 35% and 550 MPa, respectively, were used for welding stainless steel (SUS201) tubular trusses.

2.2 Material properties

As presented in Table 1, all planar square hollow stainless steel tubular trusses have the same wall thickness ($t = 2.0$ mm) and outer width of the chord ($d = 100.0$ mm) with reference to the stainless steel tube test of Hwang *et al.* [25]. All five specimens were made from Japan

Standard SUS 201 stainless steel. Similar to the study process of Reiterman *et al.* [26], the material properties of planar square hollow stainless steel tubular trusses were determined from several tensile tests. The processed tensile coupons were experimented with reference to Chinese Metallic Materials-Tensile testing at MTS displacement (GB/T228-2010) [27]. SUS 201 stainless steel has the advantages of nonmagnetic and resistance to rust and corrosion of acid and alkali. As presented in Table 2, the nominal yield stress, tensile strength, elongation, and hardness are 335 MPa, 665 MPa, 25%, and HRB90, respectively.

2.3 Test procedures and equipment

The tests were conducted in the Structures Laboratory. The schematic sketches of square hollow stainless steel tubular trusses under vertical load are shown in Figure 2. The supports and reaction frame were fastened to the

Table 2: Material properties of stainless steel SUS201

Specimens	Yield stress (MPa)	Tensile strength (MPa)	Elongation (%)	Hardness (HRB)
ST-K-B38	334	665	23	90
ST-K-B60	355	672	24	90
ST-K-B80	340	668	27	90
ST-N-B80	342	660	28	90
ST-T-B80	341	670	26	90

floor by anchor bolts with dependent performance. Hydraulic jack has a platform called a bearing pad to apply load to specimens. The size and weight of hydraulic jack meet the experimental requirements. Hydraulic bottle jacks are secured within a frame, mounted on a beam for the convenience of applying vertical loads.

In the meantime, a load cell was used to create an electrical signal whose magnitude was directly proportional to the applied force. The 320 kN capacity hydraulic bottle jack was utilized to exert the vertical load, which was monitored by the load cell. The load cell was placed concentrically between the reaction frame and the hydraulic bottle jack. The compression force was applied simultaneously at the mid-span of I steel distribution beam. The steel hinges were used at the loading points for the purpose of allowing free in-plane rotation of the trusses. Besides, steel rollers at stainless steel blocks were also used as the loading points and end supports, allowing both longitudinal displacement and rotation of specimens and thereby providing simply supported boundary conditions.

Before the test, each specimen was thoroughly cleaned on the outer surface and preloaded to make the loading machine and the truss mesh together. Then, the compression was applied continuously until truss failure. At the beginning, the load level was 10 kN, and it was changed to 5 kN when approaching the failure of the specimens. Besides, the static load was segmented at a fixed loading interval on the basis of the specimen resistance. A linear variable displacement transducer (LVDT) consisting of highly sensitive electronic sensors was used to measure linear positions. It possesses excellent characteristics of easy-to-use, stable, and accurate. The accuracy meets the

precision requirements of experiments. In this article, linear displacement was taken as the movement of the bottom chord in the vertical direction along a single axis.

Moreover, eight LVDTs served as the deflection acquisition device for the specimens with K-joints (ST-K-B38, ST-K-B60, and ST-K-B80) and seven for specimens ST-N-B80 and ST-T-B80. The mid-span deflection of the top chord was monitored by the LVDT D1, the vertical deflections at the bottom chord members and the longitudinal displacement of the end supports were monitored by other LVDTs. The arrangement of LVDTs is presented in Figure 3.

Two strain gauges were affixed to the surfaces of the braces at mid-length, which were clearly shown in Figure 3. The gauges were attached to the object by a suitable adhesive. As the specimen is deformed, the foil is deformed. The electrical resistance changes, as deformation of the foil. This resistance change, measured by the DH3816 data acquisition system, is related to the strain by the value known as the gauge factor. In this article, the type of the strain gauges is BX120-3AA and the size of the terminal block is 5×7 , in which “5” indicates that the width is 5 mm and “7” indicates that the length is 7 mm.

3 Test results

3.1 Experimental observation and failure modes

Only downward deformation was allowed in the circumstance that both ends of the specimen were fixed with

Figure 2: Test rig and specifications.

Figure 3: Arrangements of displacement transducers and strain gauges.

hinged supports. Typical failure modes were local buckling, chord bending, weld fracture, cracking, and surface plasticity explained by Gutman et al. [28]. In summary, it was found that failure modes of specimens ST-K-B38, ST-K-B60, ST-K-B80, ST-N-B80, and ST-T-B80 were different when subjected to monotonically vertical load.

Figure 4: Failure modes of the specimen ST-K-B38: (a) overview of the specimen ST-K-B38, (b) local buckling around the component “ij,” (c) weld fracture around the joint “m,” and (d) surface plasticity at the side of the bottom chord.

Taking the specimen ST-K-B38, for example, it showed linear characteristics under low vertical load at the elastic stage. As shown in Figure 1(b), the holistic deflection of the specimen subjected to the peak load of 70 kN recorded by LVDTs D2-D7 was 15.1 mm. With the piecemeal augmentation of vertical load up to 75 kN, the mid-span deflection correspondingly went up to 18.3 mm. During the loading

process, visible welding fracture occurred near the most marginal joint “m” on one side of the truss. Local buckling gradually occurred around the component “ij” of the bottom chord. In the meantime, the surface plasticity was found at the side of the bottom chord. Generally, the surface plasticity of the steel structure is always accompanied with significant outward or inward folding. As shown in Figure 4,

(a)

(b)

(c)

(d)

(e)

(f)

Figure 5: Failure modes of the specimen ST-K-B60: (a) overview of specimen ST-K-B60, (b) weld fracture of tubular joint “h,” (c) crack of the joint “m,” (d) local buckling around the component “ef,” (e) surface plasticity around the tubular joint “e,” and (f) bending of the top chord.

Figure 6: Failure modes of the specimen ST-K-B80: (a) overview of the specimen ST-K-B80 and (b) surface plasticity around the tubular joint “e.”

Figure 7: Failure modes of the specimen ST-N-B80: (a) overview of the specimen ST-N-B80, (b) surface plasticity around the tubular joint “e,” and (c) crack of the joint “e.”

the failure of this specimen was obviously triggered by local buckling of the component “ij,” and surface plasticity of the bottom chord and weld fractures occurred near the truss joint “m.”

(a)

(b)

(c)

Figure 8: Failure modes of the specimen ST-T-B80: (a) overview of the specimen ST-T-B80, (b) surface plasticity around the tubular joint “e,” and (c) cracks of the joint “e.”

For the specimen ST-K-B60 exhibited in Figure 1(c), the vertical load of 77.5 kN corresponded to the mid-span deflection of 17.8 mm, with a slight concave deformation at the top chord joint “e.” However, mid-span deflection went up 4.7 mm when the load went up 5 kN. During the loading process, surface plasticity and outward folding occurred at the bottom chord. Local buckling gradually occurred around the component “ef” of the top chord. Meanwhile, the top chord bent along the truss span. Besides, weld fractures were found around joints “h” and “m.” Furthermore, the joint “h” experienced nonvisible weld fractures around the first part section of the bottom chord. Appreciable welding cracks at joint “m” were found at the other sides of the bottom chord. Figure 5 shows the failure modes of the specimen ST-K-B60, in which the weld fractures have taken place near the joints “h” and “m,” the crack was found near the joint “m” of the bottom chord, the bending appeared at the top chord, and surface plasticity and local buckling occurred around the component “ef” of the top chord member.

For the specimen ST-K-B80 shown in Figure 1(a), the holistic deflection subjected to the peak load of 80.3 kN was 11.4 mm, accompanied by the appearance of sag,

introduced by the review of Bayock et al. [29], near the top chord joint “e,” one of the loading point. With the piecemeal augmentation of vertical load up to 97.8 kN, the mid-span deflection correspondingly went up to 16.6 mm. According to the investigation of Silin et al. [30], the final failure of the specimen was caused by

Figure 9: Total vertical load–midspan deflection curves of square hollow stainless steel tubular trusses.

Table 3: Test results of all specimens

Specimens	F_y (kN)	F_p (kN)	F_p/F_y	Δ_y (mm)	Δ_p (mm)	Δ_p/Δ_y	Failure modes
ST-K-B38	70.0	75.0	1.07	15.1	18.3	1.21	Surface plasticity + local buckling
ST-K-B60	77.5	82.5	1.06	17.8	22.5	1.26	Weld fracture + cracking + bending + local buckling + surface plasticity
ST-K-B80	80.3	98.0	1.22	11.4	16.7	1.46	Surface plasticity
ST-N-B80	85.0	100.0	1.18	11.8	16.1	1.36	Surface plasticity
ST-T-B80	70.0	86.6	1.24	14.1	22.3	1.58	Surface plasticity

Figure 10: Overall deflection of square hollow stainless steel tubular trusses: (a) truss of the specimen ST-K-B38, (b) truss of the specimen ST-K-B60, (c) truss of the specimen ST-K-B80, (d) truss of the specimen ST-N-B80, and (e) truss of the specimen ST-T-B80.

the surface plastic deformation of joint “e,” shown in Figure 6.

For the specimen ST-N-B80 shown in Figure 1(d), the holistic deflection subjected to the peak load of 85.0 kN was 11.8 mm, accompanied by the appearance of sag near the top chord joint “e,” one of the loading point. With the piecemeal augmentation of vertical load up to 100.0 kN, the mid-span deflection correspondingly went up to 16.1 mm. During the loading process, the surface plasticity was found at the side of the bottom chord, accompanied with an inward folding. Figure 7 illustrates the failure modes of the specimen ST-N-B80, in which crack and ductile deformation were found around the tubular joint “e” of top chord and the appearance of the bottom chord, respectively.

For the specimen ST-T-B80 shown in Figure 1(e), the holistic deflection subjected to the peak load of 70.0 kN was 14.1 mm. With the piecemeal augmentation of vertical load up to 86.6 kN, the mid-span deflection correspondingly went up to 22.3 mm. In the meantime, the surface plasticity

was found at the side of the bottom chord, accompanied with an inward bulging. Appreciable cracks were found in the joint “e,” where part of the axial pressure acted. Clearly, the invalidity of the component was also due to ductile deformation and cracks near the chord joint, as shown in Figure 8.

It was demonstrated by Fong et al. [31] that the bending, local buckling, weld fracture, and surface plasticity were the main reasons for the failure of steel tubular trusses. Based on the test results, it is found that all specimens experienced surface plasticity, which was also found by Guo et al. [32]. Moreover, the failure of specimens ST-K-B38, ST-K-B80, ST-N-B80, and ST-T-B80 came from various forms of connection damage at the loading position. It is quite evident that failure modes of specimens ST-K-B38 and ST-K-B60 were different from that of other trusses. Furthermore, weld fractures of specimens ST-K-B38 and ST-K-B60 occurred at the location of the tubular joint on the bottom chord. The invalidity of these two specimens was caused by local buckling of truss connections.

Table 4: Deflection of the tubular joints at the bottom chord members of all specimens

Specimens	Loads (kN)											Joints
	10	20	30	40	50	60	70	75	80	85	90	
	Deflection (mm)											
ST-K-B38	0.7	1.3	2.1	2.9	4.1	5.5	7.7	9.6	—	—	—	h
	0.8	1.5	2.4	3.5	4.9	6.5	9.0	11.3	—	—	—	i
	0.9	1.8	2.9	4.0	5.5	7.3	10.0	12.4	—	—	—	j
	1.0	1.9	3.0	4.1	5.6	7.1	9.7	12.0	—	—	—	k
	1.0	1.9	2.7	3.6	5.0	6.2	8.4	10.2	—	—	—	l
	0.7	1.4	2.1	2.9	3.9	4.9	6.5	7.9	—	—	—	m
ST-K-B60	0.4	0.9	1.4	1.9	2.7	3.4	4.5	5.2	7.6	—	—	h
	0.7	1.4	2.2	3.1	4.3	5.6	7.3	8.4	12.5	—	—	i
	0.8	1.7	2.7	3.9	5.4	7.0	9.1	10.3	15.7	—	—	j
	0.7	1.8	2.8	3.9	2.2	6.8	8.9	10.1	16.2	—	—	k
	0.7	1.4	2.2	3.3	4.4	5.8	7.3	8.3	14.2	—	—	l
ST-K-B80	0.6	1.1	1.6	2.2	3.0	3.7	4.7	5.3	9.8	—	—	m
	0.3	0.7	1.1	1.5	2.0	2.4	2.9	3.3	3.5	3.8	4.1	h
	0.7	1.3	2.0	2.8	3.6	4.5	5.4	6.0	6.5	7.1	7.8	i
	0.9	1.7	2.7	3.6	4.7	5.8	7.0	7.8	8.5	9.3	10.2	j
	0.7	1.8	2.7	3.7	4.8	5.9	7.3	8.0	8.7	9.4	10.5	k
	0.8	1.6	2.4	3.2	4.0	5.0	6.1	6.7	7.3	7.9	8.7	l
ST-N-B80	0.6	1.2	1.5	2.2	2.5	3.2	3.6	4.2	4.5	4.8	5.2	m
	0.6	1.2	1.7	2.2	2.9	3.4	4.1	4.4	4.8	5.1	5.5	h
	0.9	1.7	2.5	3.4	4.3	5.2	6.2	6.7	7.3	7.9	8.6	i
	1.0	1.9	2.7	3.9	4.7	5.9	6.8	7.4	8.1	8.8	9.7	j
	0.8	1.7	2.4	3.3	4.2	5.2	6.0	6.6	7.2	7.8	8.5	k
ST-T-B80	0.6	1.2	1.7	2.3	2.9	3.5	4.1	4.4	4.7	5.1	5.5	l
	0.5	1.0	1.6	2.2	2.8	3.6	4.4	4.8	5.2	5.7	—	h
	1.2	2.3	3.7	5.1	6.6	8.3	10.4	11.5	12.7	14.0	—	i
	1.4	2.9	4.7	6.4	8.5	10.6	13.3	14.7	16.4	18.1	—	j
	1.4	2.6	4.1	5.6	7.3	9.0	11.2	12.3	13.8	15.2	—	k
	0.6	1.3	1.9	2.6	3.3	4.1	5.0	5.5	6.0	6.6	—	l

Figure 11: Weight per unit load-carrying capacity of trusses (F/G).

3.2 Load (F) versus mid-span deflection (Δ_m) curves

The vertical load (F) versus mid-span deflection (Δ_m) curves are presented in Figure 9. The data of vertical displacement were recorded automatically by LVDTs. It

can be defined that the trial deflection value of the bottom chord approximates to the overall truss deflection according to Sun *et al.* [33]. The effects of different variables on all specimens are discussed as follows.

It was shown from the comparison that almost all of the truss specimens under vertical loads experienced three stages: elastic stage, elastic-plastic stage, and ultimate stage. Nobre *et al.* [34] proposed a method for the analysis of “KK” joints with circular hollow cross sections. Two distinct points that represent the yield load (F_y) and the peak load (F_p) were marked as “◇” and “×,” respectively, in each curve, as shown in Figure 9. Peak load–yield load ratio (F_p/F_y) and peak–yield deflection ratio (Δ_p/Δ_y) in the section of middle of span are presented in Table 3. Through the contrastive analysis, values of the ratio (Δ_p/Δ_y) of specimens ST-T-B80, ST-K-B80, ST-N-B80, ST-K-B60, and ST-K-B38 are found in the descending order, indicating that specimen ST-T-B80 features the most considerable ductility. What’s more, the ductility of specimens ST-N-B80 and ST-K-B80 decreased by 17 and 8% compared with the specimen ST-T-B80, respectively.

Table 5: Strain development of specimens with K-joints

Strains (μ) Members	Specimens								
	ST-K-B38			ST-K-B60			ST-K-B80		
	Loads								
	30 kN	50 kN	70 kN	30 kN	50 kN	70 kN	30 kN	50 kN	70 kN
ab	−87.0	−136.5	−169.5	−81.5	−140.5	−186.5	−97.9	−160.1	−234.8
bc	−190.0	−314.0	−448.5	−87.5	−124.0	−144.0	−193.8	−321.8	−486.3
cd	−220.5	−361.5	−500.0	−162.5	−265.5	−363.0	−219.8	−365.1	−535.3
de	−174.0	−346.5	−477.5	−134.0	−214.0	−279.5	−246.3	−393.7	−563.5
ef	−216.0	−361.5	−557.0	−169.5	−291.5	−437.5	−230.5	−387.6	−608.5
fg	−69.0	−124.0	−169.0	−27.0	−54.0	−76.5	−91.8	−149.9	−207.5
hi	158.0	241.5	327.0	149.5	227.5	278.0	156.5	258.5	356.5
ij	246.0	391.5	540.5	279.0	428.5	572.0	240.2	395.2	542.3
jk	280.0	455.5	639.0	245.5	366.0	476.0	251.4	420.2	584.7
kl	260.0	417.5	578.5	290.5	447.5	601.0	234.6	385.0	524.1
lm	153.0	251.0	344.0	144.0	206.5	271.5	155.5	255.0	349.4
ah	382.0	638.0	867.5	217.0	373.5	513.5	171.3	281.0	383.8
bh	−307.0	−504.0	−688.0	−165.0	−265.0	−359.0	−130.0	−213.1	−299.4
bi	179.0	283.0	393.0	120.5	201.5	274.5	108.1	174.4	232.3
ci	−208.5	−356.0	−501.0	−120.5	−184.0	−253.0	−114.7	−189.2	−258.5
cj	−1.5	15.0	44.0	47.5	80.5	121.0	22.4	45.3	69.6
dj	−101.0	−169.0	−227.0	−51.0	−91.5	−134.0	−13.2	−26.5	−45.9
dk	−88.0	−170.0	−199.5	−19.5	−47.0	−65.5	−35.1	−55.5	−62.1
ek	8.0	27.5	54.0	38.5	71.0	113.5	14.2	33.6	54.5
el	−192.5	−313.5	−424.5	−122.5	−211.0	−288.5	−105.0	−169.8	−232.8
fl	159.5	260.0	362.5	112.5	154.5	207.5	98.9	164.7	223.2
fm	−288.5	−481.0	−678.5	−159.5	−268.5	−368.5	−111.1	−187.1	−262.6
gm	333.0	565.5	791.5	181.5	272.5	359.0	175.9	292.2	408.0

Table 6: Strain development of the trusses with different outer width

Strains (<i>u</i>) Members	Specimens								
	ST-K-B80			ST-N-B80			ST-T-B80		
	Loads								
	30 kN	50 kN	70 kN	30 kN	50 kN	70 kN	30 kN	50 kN	70 kN
ab	−97.9	−160.1	−234.8	−142.5	−243.0	−328.5	−167.0	−298.5	−444.5
bc	−193.8	−321.8	−486.3	−235.0	−387.5	−555.0	−180.5	−319.5	−453.0
cd	−219.8	−365.1	−535.3	−250.0	−402.0	−541.0	−188.0	−337.0	−518.5
de	−246.3	−393.7	−563.5	−264.5	−446.5	−609.5	−170.0	−285.5	−423.5
ef	−230.5	−387.6	−608.5	−237.0	−388.5	−558.0	−156.0	−264.5	−380.0
fg	−91.8	−149.9	−207.5	−146.0	−244.5	−331.0	−108.0	−142.5	−187.0
hi	156.5	258.5	356.5	171.0	273.5	392.0	198.5	326	447.0
ij	240.2	395.2	542.3	267.5	435.0	608.0	214.5	365.0	532.0
jk	251.4	420.2	584.7	268.0	427.5	596.5	191.0	314.5	443.5
kl	234.6	385.0	524.1	164.5	281.0	472.5	177.5	305.0	425.0
lm	155.5	255.0	349.4	—	—	—	—	—	—
ah	171.3	281.0	383.8	236.0	400.5	549.5	332.5	529.0	761.0
bh	−130.0	−213.1	−299.4	−88.0	−147.5	−209.0	−75.5	−136.0	−174.0
bi	108.1	174.4	232.3	123.0	206.5	269.5	—	—	—
ci	−114.7	−189.2	−258.5	−80.5	−119.0	−157.0	−31.0	−68.5	−89.5
cj	22.4	45.3	69.6	17.5	38.0	58.0	—	—	—
dj	−13.2	−26.5	−45.9	−19.0	−20.0	−51.0	3.5	−25.0	−39.5
dk	−35.1	−55.5	−62.1	—	—	—	—	—	—
ek	14.2	33.6	54.5	−110.0	−158.0	−217.0	−38.5	−78.0	−105.0
el	−105.0	−169.8	−232.8	—	—	—	—	—	—
fl	98.9	164.7	223.2	−105.0	−157.5	−224.5	−50.5	−136.0	−158.0
fm	−111.1	−187.1	−262.6	—	—	—	—	—	—
gm	175.9	292.2	408.0	—	—	—	—	—	—
ej	—	—	—	6.5	26.5	40.0	—	—	—
fk	—	—	—	124.0	213.0	283.0	—	—	—
gl	—	—	—	176.5	314.5	431.5	331.5	528.0	757.0

+: tensile strain
-: compressive strain

Figure 12: Strain direction of the truss components: (a) K-joint, (b) T-joint, and (c) N-joint.

Therefore, it was observed that the ductility of truss with T-joint is better than that with N-joint or K-joint. In the meantime, the ductility of specimens ST-K-B38 and ST-K-B60 decreased by 21 and 16% compared with that of the specimen ST-K-B80, respectively. Hence, the ductility of trusses with K-joint was found to increase with the increase of outer width (D) of the brace members varying from 38 to 80 mm.

Yusouf *et al.* [35] evaluated the load–deflection curve of the optimal slope for the calculation of Young's modulus of bending. Through the determination of the approximate straight line segment of the load versus deflection curves, it can be considered that all trusses ended the elastic stage before the load reached 70 kN. Moreover, the elastic rigidity ratio of specimens ST-K-B80, ST-N-B80, ST-K-B38, ST-K-B60, and ST-T-B80 is 1.45:1.43:1.30:1.28:1.00. Upon further loading, all trusses entered the elastic–plastic stage, thereby leading to non-uniform changes of flexural rigidity illustrated in the experimental investigation of Xian *et al.* [36]. It was

observed that the flexural rigidity of truss with the N-joint is better than that with the K-joint or T-joint. Furthermore, the flexural rigidity of specimen ST-K-B80 is better than that of other specimens with the K-joint. In the meantime, it is not hard to find from Figure 9 that the load versus deflection curves of specimens ST-T-B80, ST-K-B80, and ST-N-B80 have the obvious postultimate stage, while specimens ST-K-B60 and ST-K-B38 do not have this stage, which is manifested in the experimental phenomenon that the latter two specimens suddenly failed as soon as the load increased to the peak value (F_p). The overall deflection curves of all tested trusses differing in the load level are illustrated in Figure 10. Obviously, the overall deflection curves of all trusses are similar, which are presented in half sine wave explained in the microstructural evolution of Zarchi *et al.* [37], as shown in Figure 10.

Deflections of the tubular joints at the bottom chord of all specimens are presented in Table 4. The results

Figure 13: Load–strain curves of the specimen ST-K-B38: (a) load–strain curves of top chord, (b) load–strain curves of bottom chord, and (c) load–strain curves of brace.

indicate that the deflection of each bottom chord is also in symmetry along the truss span. Before the load did not reach 30 kN, specimens were within the elastic stage, and the overall deflection was primarily caused by the vertical displacement of bottom chords ranging from 0 to 1/7 of the span. As vertical loads gradually increased, the vertical displacement of the trusses in the span range from 1/7 to 3/7 had a sharp growth found in the investigation of Tiainen et al. [38]. There were no obvious deflections of specimens before the failure of specimens, whereas right after the failure of specimens, there were evident deflections of specimens. Therefore, the overall deflections of the specimen ST-K-B60 are bigger than that of specimens ST-K-B38, ST-K-B80, ST-N-B80, and ST-T-B80. When specimens ST-K-B38, ST-K-B60, ST-K-B80, ST-N-B80, and ST-T-B80 were subjected to loads less than 70.0, 77.5, 81.1, 85.0, and 70.0 kN, respectively, the overall deflection increased uniformly, as shown in Figure 9. It can be found that specimens ST-K-B38, ST-K-

B60, ST-K-B80, ST-N-B80, and ST-T-B80 entered the elastic-plastic stage, when the total vertical load was beyond 70.0, 77.5, 81.1, 85.0, and 70.0 kN, respectively. The behavior of the shear panel damper studied by Shi et al. [39] was mainly in the elastic-plastic stage.

3.3 Load-carrying capacity

Table 3 presents the yield loads (F_y) and the peak loads (F_p) of all the tested specimens. The effects of different variables are discussed in this section:

It should be noted that F_p of specimens ST-K-B38, ST-K-B60, ST-K-B80, ST-N-B80, and ST-T-B80 increased by 7, 6, 22, 18, and 24% from the F_y , respectively, which the specimen ST-T-B80 had relatively larger safety margin, which was investigated by Mkrtychevand and Bulushev [40]. Hence, F_y of specimens ST-N-B80, ST-K-B80, ST-K-

Figure 14: Load-strain curves of the specimen ST-K-B60: (a) load-strain curves of top chord, (b) load-strain curves of bottom chord, and (c) load-strain curves of brace.

B60, ST-K-B38, and ST-T-B80 are in a descending order. F_p of specimens ST-K-B38, ST-K-B60, ST-T-B80, ST-K-B80, and ST-N-B80 are in an ascending order. Obviously, F_y and F_p of the specimen ST-N-B80 are the highest when comparing with that of other specimens. Significant differences in the load-carrying capacity were observed among the tested specimens due to the variation of the types of joints and the different outer widths of brace members.

In the meantime, it is shown from the comparison that F_y of specimens ST-K-B38 and ST-K-B60 are smaller than that of the specimen ST-K-B80 by 15 and 4%, respectively. F_p of these two trusses are smaller than that of the specimen ST-K-B80 by 31 and 19%, respectively. Hence, F_y and F_p of the truss with K-joints were found to increase with the increase of outer width (D) of the brace members varying from 38 to 80 mm. Besides, it is shown from the comparison that F_y values of specimens ST-K-B80 and ST-T-B80 are smaller than that of the specimen ST-N-

B80 by 6 and 21%, respectively. F_p values of these two trusses are smaller than that of the specimen ST-N-B80 by 2 and 15%. Therefore, it was observed that the F_y and F_p of the truss with N-joint (ST-N-B80) are better than that of the specimen with K-joint (ST-K-B80) or T-joint (ST-T-B80).

On the other side, the utilization rate of the material strength of different types of planar square hollow stainless steel tubular trusses was evaluated by contrasting their load-carrying capacity (F) per unit weight (G), as shown in Figure 11. The concept of the strength-to-weight ratio was introduced by Abdullah and Hassan [41]. It was observed through the contrast that the values of the ratio F/G of all the tested specimens ST-T-B80, ST-N-B80, ST-K-B80, ST-K-B38, and ST-K-B60 diminish progressively. In other words, the specimen ST-T-B80 enjoys the best efficiency in practice, attributed to the highest ratio of strength to weight, among the five tested specimens. It is shown that the ratio of strength to weight of specimens

Figure 15: Load-strain curves of the specimen ST-K-B80: (a) load-strain curves of top chord, (b) load-strain curves of bottom chord, and (c) load-strain curves of brace.

ST-K-B60 and ST-K-B38 is smaller than that of the specimen ST-K-B80 by 5 and 1%. The specimen with largest brace outer width among three tested K-joint trusses has the best utilization rate of material strength. Besides, the ratio of specimens ST-K-B80 and ST-N-B80 is smaller than that of the specimen ST-T-B80 by 28 and 4%, respectively, that is, the load-carrying capacity per unit weight of the specimen with T-joint (ST-T-B80) is better than that of with N-joint (ST-N-B80) or K-joint (ST-K-B80).

3.4 Load versus strain curves

The tensile strain of all specimens under different loads is presented in Tables 5 and 6. Strain (ϵ) represents the value of the micro-strain, which was investigated in the material research of Guo et al. [42]. A negative strain denotes a compressive strain, while a positive strain

denotes a tensile strain. As expected, the strain reflects that the top chords were compressed, bottom chords were tensioned, and the braces bore the mixed action of tension and pressure. The principle of the key elements based on the global stiffness matrix in the work of Feng et al. [43] can be used in safety assessment for truss structure. Through analyzing the experimental result of the brace member for each truss, the tensile strain of specimens with K-joint (ST-K-B38, ST-K-B60, and ST-K-B80) was detected on the components “ah,” “bi,” “cj,” “ek,” “fl,” and “gm.” The compressive strain was detected on the components “bh,” “ci” and “dj,” “dk,” “el,” and “fm.” For the specimen with T-joint (ST-T-B80), the tensile strain was detected on the component “ah” and “gl.” The compressive strain was detected on the components “bh,” “ci,” “dj,” “ek,” and “fl.” For the specimen with N-joint (ST-N-B80), the tensile strain was detected on the component “ah,” “bi,” “cj,” “ek,” “fl,” and “gm.” The compressive strain was detected on the components “bh,” “ci,” “dj,” “ek,” and “fl.” Figure 12 summarizes the

Figure 16: Load-strain curves of the specimen ST-N-B80: (a) load-strain curves of top chord, (b) load-strain curves of bottom chord, and (c) load-strain curves of brace.

Figure 17: Load–strain curves of the specimen ST-T-B80: (a) load–strain curves of top chord, (b) load–strain curves of bottom chord, and (c) load–strain curves of brace.

strains of these components. The strain intensity of all specimens is shown in Figures 13–17. By contrast, the compressive and tensile strains of trusses is also in symmetry along the truss span. In consideration of the geometric symmetry, the other half of the load versus strain curves has a similar rule in principle.

For the top chord of specimens ST-K-B38, ST-K-B60, ST-K-B80, and ST-T-B80, presented in Tables 5 and 6, the axial strains of component “cd” exceed those of components “ab” and “bc.” For the top chord of specimen ST-N-B80, presented in Table 6, the axial strains of component “bc” exceed those of components “ab” and “cd.” Hence, for the component “cd” of trusses with K-joint, as shown in Figure 18(a), the initial slopes of curves for ST-K-B60 are larger than those of specimens ST-K-B80 and ST-K-B38. In addition, the curves of specimens ST-K-B38, ST-K-B60, and ST-K-B80 are in linear stage under 30kN. The component “cd” in the top chord of specimens with K-joints (ST-K-B38, ST-K-B60, and ST-K-B80) and T-joint

(ST-T-B80), which has the maximum axial strains located at the position between 3/7 and 4/7 of the truss span along the top chord. The component “bc” in the top chord of specimens with N-joints (ST-N-B80), which have the maximum axial strains located at the position between 2/7 and 3/7 of truss span along the top chord.

In terms of the bottom chord for trusses ST-K-B38, ST-K-B60, and ST-K-B80, axial strains of component “jk” exceed those of components “hi” and “ij.” In terms of the bottom chord for trusses ST-N-B80 and ST-T-B80, axial strains of component “ij” exceed those of components “hi.” Hence, for the component “jk” of trusses with K-joint, as shown in Figure 18(b), the initial slopes for curves of ST-K-B80 are larger than those of specimens ST-K-B38 and ST-K-B60. Furthermore, the curves of ST-K-B38, ST-K-B60, and ST-K-B80 are in the linear stage under 30 kN. The component “jk” in the bottom chord of specimens with K-joints (ST-K-B38, ST-K-B60, and ST-K-B80) has the maximum axial strains located at the

Figure 18: Comparison of load–axial strain relationship for components “cd,” “jk,” and “ah” in different trusses: (a) component “cd” in trusses with K-joints, (b) component “jk” in trusses with K-joints, (c) component “ah” in trusses with K-joints, and (d) “ah” bracing member for “N,” “T,” and “K” joints.

position between 3/6 and 4/6 of truss span along the bottom chord. The component “ij” in the bottom chord of specimens with N-joint (ST-N-B80) and T-joint (ST-T-B80) has the maximum axial strains located at the position between 2/5 and 3/5 of truss span along the bottom chord. Chuannan [44] proposed a formula for calculating the yield capacity and ultimate bearing capacity of CFRP-reinforced axially compressed round tube short column.

Besides, for the brace members of all specimens, axial strains of component “ah” exceed those of other components. Hence, for the component “ah” of trusses with K-joint shown in Figure 18(c), the initial slopes of the test curves of specimens ST-K-B80 are larger than those of specimens ST-K-B38 and ST-K-B60. Also, the test curves of specimens ST-K-B38 and ST-K-B80 are in the linear stage. For the component “ah” of trusses with different joint types, as shown in Figure 18(d), the initial

slopes for ST-K-B80 are larger than those of specimens ST-N-B80 and ST-T-B80. In addition, the test curves of specimens ST-K-B80, ST-N-B80, and ST-T-B80 develop in a linear stage under 30 kN. The component “ah” in brace of specimens with K-joints (ST-K-B38, ST-K-B60, and ST-K-B80), N-joint (ST-N-B80), and T-joint (ST-T-B80), which have the maximum axial strains, is located at the position between 1/7 and 2/7 of truss span along the top chord.

4 Conclusion

The failure modes, ultimate bearing capacity, ductility, and axial strains of specimens ST-K-B38, ST-K-B60, ST-K-B80, ST-N-B80, and ST-T-B80 were the major research

objects. In the light of study results, the conclusions are as follows:

1. Chords of all specimens experienced surface plasticity. The failure of most of the tested specimens was triggered by the local buckling of the connection between the top chord and the brace directly, which was directly subjected to load.
2. The specimen ST-T-B80 has the best ductility. The ductility of truss with T-joint is better than that of specimens with N-joint or K-joint. The ductility of trusses with K-joint was found to increase with the increase of outer width (D) of the brace members. The flexural rigidity of truss with K-joint is better than that of specimens with N-joint or T-joint.
3. The load-carrying capacity per unit weight of trusses with K-joints was found to increase with the increase of outer width (D) of the brace members. Also, the strength-to-weight ratio of the specimen with T-joint is better than that of specimens with N-joint or K-joint (ST-K-B80).
4. The components “cd” in the top chord, “jk” in the bottom chord, and “ah” in brace of K-joint specimens, which have the maximum axial strains, are located at the position from 3/7 to 4/7, 3/6 to 4/6, and 1/7 to 2/7 of the truss span along the top chord, respectively.

Nomenclature

t_0	chord wall thickness
w	weld sizes
D	outer width of the brace
w	weld sizes
f_y	yield stress
F_y	yield loads
F_p	peak loads
F	vertical load
Δ_y	midspan deflection corresponding to the yield load
Δ_p	midspan deflection corresponding to the peak load
Δ_m	midspan deflection
Δ	vertical deflection
G	weight

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