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Experimental research and theoretical study on bending capacity of tube-gusset K-joint connection

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This study investigates bending behavior of tube-gusset K-joint using static experimental research and finite element analysis (FEA). Firstly, five groups of full scale tube-gusset K-joint models with different parameters which mainly refer to diameter and thickness of main tube were carried out to study the response and bearing condition of nodes in loading process. Then, finite element model of the joint was established, and the influence of main parameters including diameter and thickness of main tube, and length of gusset on the node mechanical performance was studied. Test and FEA results show that node bending capacity decreases with the increment of main tube diameter and increases with the increment of the main tube thickness and gusset length. On the basis of experimental and theoretical analysis, bending capacity calculation formulas of tube-gusset k-joint were proposed with numerical method and its applicability is verified.

Key words: Tube-gusset K-joint, static experiment, finite element analysis, bending capacity.

INTRODUCTION

Steel component with pipe cross section has many advantages, for instance, larger in radius of gyration and torsional stiffness, no weak axis under bending moment, high bearing capacity and good corrosion resistance after port closed, etc (Wang, 2011). Tube-gusset joint is mainly made up of steel tube and has above advantages, which avoid complex process of tubular welding joint and has better bearing performance; hence it is widely applied in hollow section structures. At present, tube-gusset joint is one of main node forms in industrial and civil constructions (Luo, 2010), which is being applied in practical engineering as shown in Figure 1.

Throughout specifications of hollow section structure at home and abroad, theoretical study and experimental research have rarely been done; mature design formula for the node has not been proposed yet. Engineers always refer to tubular node and consider certain safety factors when designing this type of node. Theoretical study and experimental research in-depth are needed.

Access to the data referred by the author and relevant research to this paper mainly includes: reduced scale experiment of tubular node which forced simultaneous on main tube and branch tube has been carried by Kim (2001); and established finite element model which replace axial force of branch tube by equivalent loads, on the basis of preceding work, calculation method of branch tube axial force and node moment was proposed; deduced dimensionless interactional relation of main tube

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(a)

(b)

Figure 1. Practical use of the node in engineering (a) truss (b) Transmission line tower.

axial force, component of branch tube axial force along main tube direction and node moment. Wang et al. (2000) studied stress distribution of tubular K-joint by FEA method, analyssed parameters which influence the node bearing capacity and concluded infinite element calculation formula of tubular K-joint. All above researches focus on experiment research and FEA of tubular welding node; experimental research and theoretical analysis of full scale tube-gusset joint has not been found in references; and practical design formula of tube-gusset node is still in blank.

The purpose of this research is to acquire the node mechanical performance under static load and calculation formula. Firstly, finite experiment of full scale tube-gusset K-joints have been done; thereafter FEA models of the nodes were founded and calculated; and finally, practical bending capacity calculation formula of tube-gusset K-joint through numerical regression analysis method concluded the study.

SUMMARY OF TEST

Specimens design

Five groups (K1 to K5) specimens have been designed. To avoid coincidence from a single result, each group has two identical specimens in same test process, and average value of each group was adopted for the following analysis.

The mainly relevant parameters in experiment are diameter and thickness of main tube. To study the failure mechanization of node area, stiffness of gusset and branch tube should be enough to the extent that would not damage before main tube. The specimens have three different main tube thicknesses: t (6 , 8 and 10 mm), main tube diameter, D (152, 168 and 219 mm). All gussets in specimens are unified 380 × 140 × 12 mm; the size of branch tube $d_z \times t_z$ are all 95 × 10 mm; angle between main and branch tube is maintained at 60°. Basic parameters of the specimens are given in Table 1. The node dimension is as shown in Figure 2.

Main tube and gusset were connected through fillet weld, while branch tube and branch plate were connected by open welding. Geometric size and structure of K1 is shown in Figure 2.

Property of the material

All specimens were made of Q235. Four standard test samples were fabricated by scrap reserved in baiting process and average test results were taken as the specimens mechanical property as shown in Table 2.

Load application

The test was carried out in Beijing University of Civil Engineering. The adopted load application facility was 500 KN hydraulic jack and self-balanced loading frame. In order to imitate the model which was destroyed under bending moment in reality, load was applied to the bottom of main tube horizontally by jack, which is one-way loading by steps (studied node mechanical property under bending). Loading devices are shown in Figure 3.

Ultimate load was obtained when load-displacement curve of main tube skin point to where transformed maximum emerged, with the decreased part or deformation value in this paper surpassing ultimate deformation (3% diameter of main tube) (Zhao, 1995; Van der Vegte, 1995). As location of decrease point was hardly determined, the later criterion was used as basis for judgment.

Two control modes including force control and displacement control were employed in load application process; the specific steps taken are as follows: 10 KN applied in first loading stage, increment of following stages are 5 KN, and displacement jumped when load was applied up to 60 KN; thereafter, there was a reverse to adopt displacement control with 10 mm added to original deformation in the first stage, the following increments 5 mm (the strain of measuring point remaining unchanged); every stage was

Table 1. Basic parameters of test specimens.

Specimen	*L* (mm)	*t* (mm)	l_z (mm)	d_z (mm)	D (mm)	θ (°)	Boundary of non-loading end	Amount of specimens
K1	1200	6	304	95	168	60	fixed	2
K2	1200	8	304	95	168	60	fixed	2
K3	1200	10	304	95	168	60	fixed	2
K4	1200	6	304	95	152	60	fixed	2
K5	1200	6	304	95	219	60	fixed	2

Table 2. Mechanical property of material.

Type of steel	Yield strength (f_y/MP)	Tensile strength (f_t/MP)	Elongation percentage (ε/%)
Q235	284.3	470.8	29.4

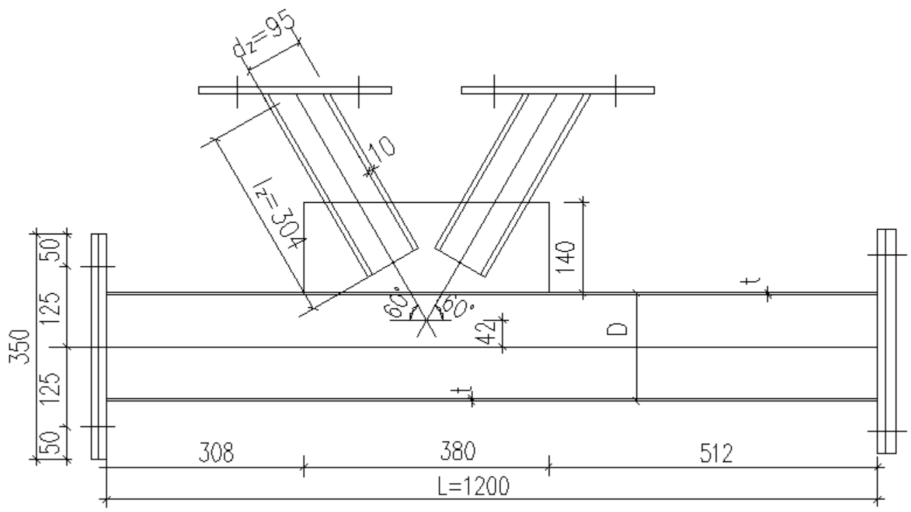


Figure 2. Size of node.

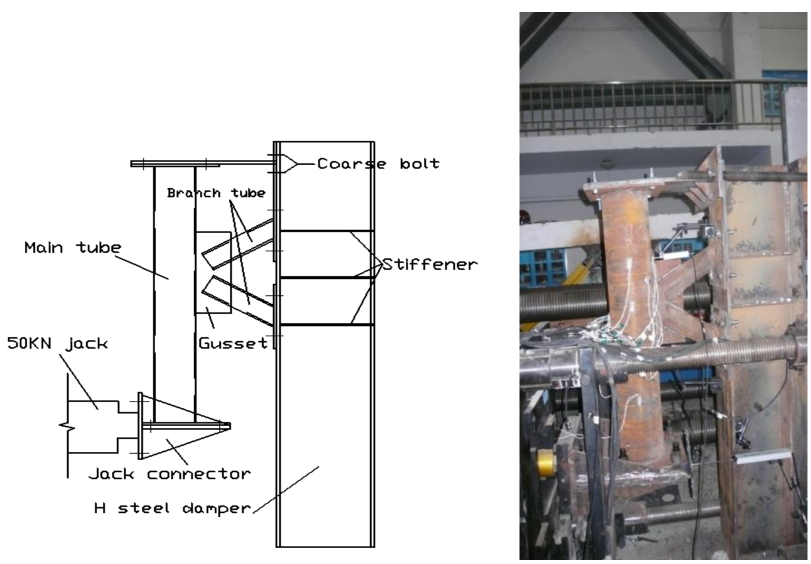


Figure 3. Test loading mode.

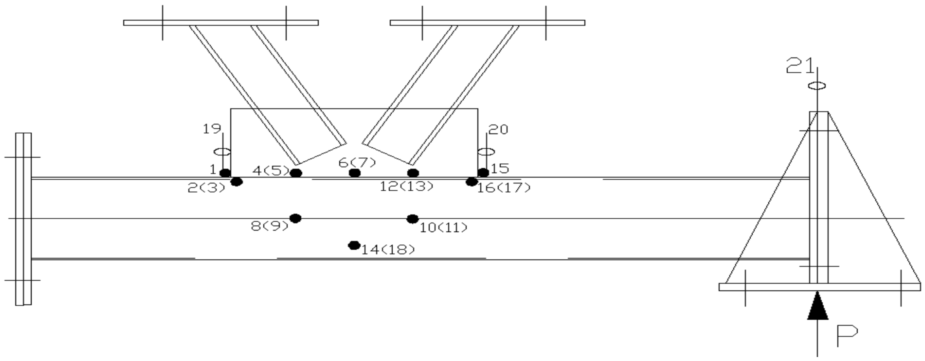
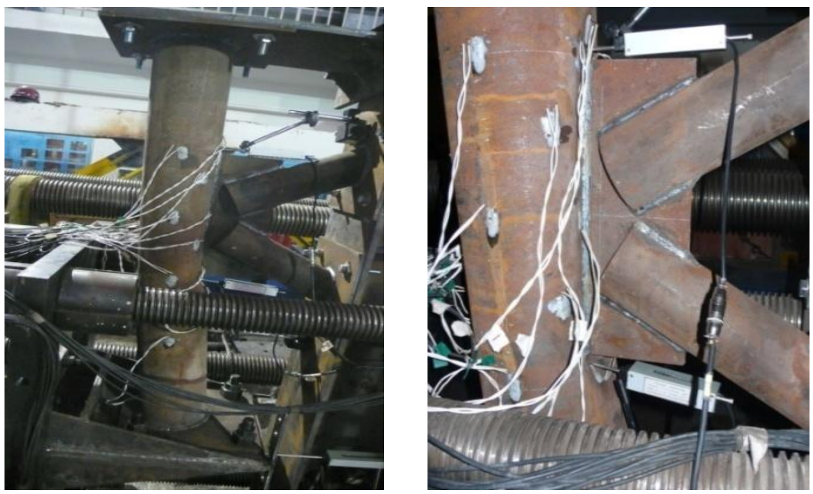


Figure 4. Layout of measuring points.



(a) (b)

Figure 5. Deformation graph of K2 after failure (a) Global deformation (b) Local deformation.

kept static for two minutes before being entered into next stage. The entire process lasted about 2 h for one specimen.

Measuring point arrangement

Strain gauges (1~3, 15~17) were glued at connection part measuring change of strain, gauges (4-14, 18) were glued around the joint and in scope of 0.5 length of branch tube. Displacement meters (19, 20) was arranged at the connection, 19 measures local deflation deformation of the joint, 20 measures depression deformation of the joint, 21 measures displacement of loading end. Measuring points distributed shown in Figure 4, revealed 1~18 and 19 are strain gauges, and 21 represent displacement meter.

TEST RESULTS

Deflation deformation

The largest bending moment emerges in connection between main tube and gusset when horizontal force was applied on one end of main tube; because of small area in connection, stress concentration occurs in this place. Taking K2 as an example, the yield load is about 65 KN. This does not mean that further load increase will result to destruction as plastic stress redistribution take place in this region; though there will be node failure when local plastic deformation is too large. The failure load is about 103 KN. Local denting can be seen in compression side after joint failure, meanwhile, deflation deformation can be seen in tension side, specimen K2 after failure as shown in Figure 5.

Local denting

The test result is as shown in Table 3. Among them, refers to the replacement of 21, *M* refers to the moment of measuring point, and *s* refers to the deformation of 20.

Table 3. Measurement result in loading stages of K2.

P (kN)	Δ (mm)	M (kN•m)	s (mm)
4.95	0.43	2.534	0.086
66.5	7.91	34.048	1.511
102.27	26.93	52.364	5.038
140.7	41.84	72.038	8.224

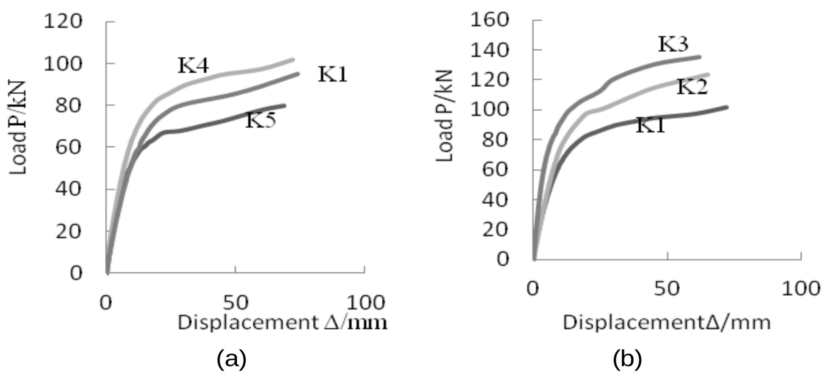


Figure 6. Stress-strain curves (a) Alter diameter of main tube (b) Alter thickness of main tube.

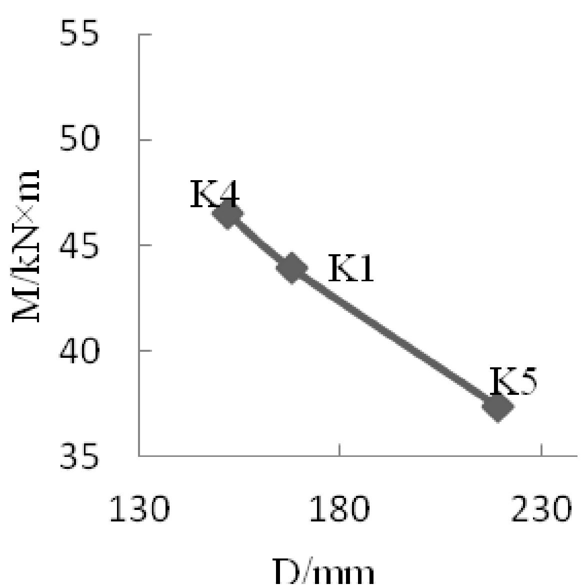


Figure 7. Variation of ultimate strength main tube with diameter.

Load-Displacement curve

The load-displacement curves of specimens under loading are as shown in Figure 6; force and displacement are in linear relationship at the beginning of load application, which indicate that specimens are in elastic stage, transferred to plastic stage with larger load application, faster increasing deformation of specimens, but small increment of bearing capacity of specimens.

Figure 6(a) shows bearing capacity decreases with increment of main tube diameter while 6(b) shows increases with increment of main tube thickness.

Parameters analysis of test result

The influence of main tube diameter on bearing capacity shown in Figure 7 reveals joints bearing capacity decrease with the increment of main tube diameter.

The influence of main tube thickness on bearing capacity shown in Figure 8 reveals joints bearing capacity increase with the increment of main tube thickness. Specimens were yield successive as load increased instantly, promoting bending rigidity as the increment of main tube thickness; therefore resulting in larger bearing capacity.

INFINITE ELEMENT ANALYSES

Established infinite element analytical models

Infinite element models adopted unit-solid 45 to imitate this type of unite combined with 8 nodes; each node has three translational freedom degrees along coordinate direction of *x*, *y*, *z*. Q235 was selected as material of

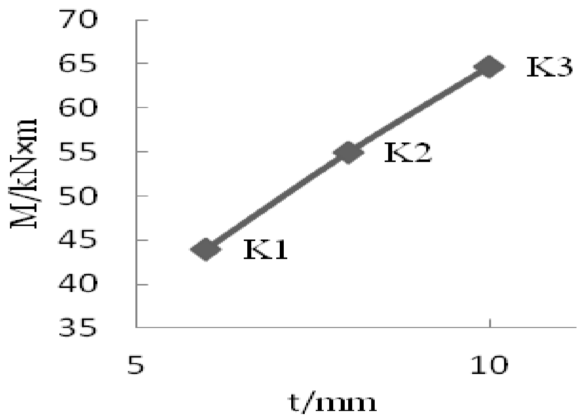


Figure 8. Variation of ultimate strength with main tube thickness.

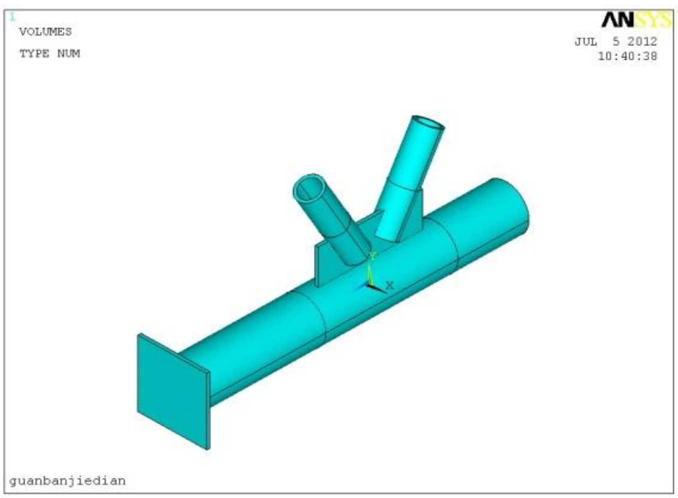


Figure 9. Finite element analysis model.

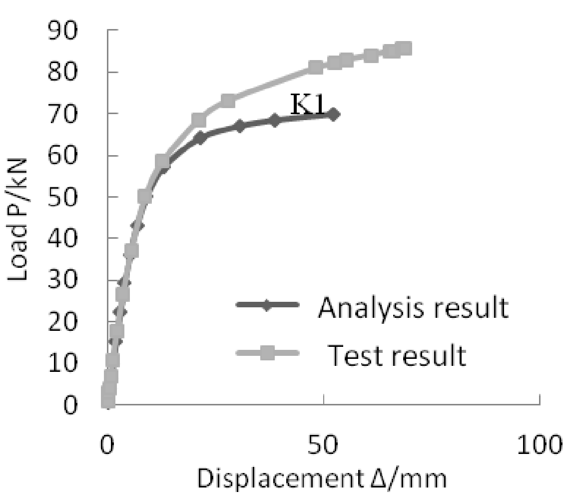


Figure 10. Stress-strain curves of specimen K1.

models, referring to the test result, valued at E=2.05×10^5 N/mm^2, v=0.29, abide by Von-Mises yield criterion and associated flow rules, plastic models sizes, boundary conditions and means of applying load was kept the same as the tests have been done. Main tube node area was subdivided in the process of meshing; branch tube and gusset adopted intelligent mesh; number of main tube element is 3344, while total element of the model is 6762. Weld has not been simulated, as benefit effect and bad effect of residual stress on bearing capacity are basic equivalent. Model is shown in Figure 9. Bearing capacity was judged by ultimate deformation criterion, namely deformation of hot point reached 3% main tube diameter.

Comparison study of FEA to test result

In order to verify reliability of FEA result, comparison of calculation result to results of FEA and test is shown in Table 5. Result of FEA was a bit smaller than that of test in certain range. FEA result and test result of K1 are shown in Figure 10; stress and strain in FEA models well imitated actual process.

Major influential parameters

There are plenty of influential parameters to tube-gusset K-joint, including length, thickness and diameter of main tube; length and thickness of gusset; diameter, thickness and angle of branch tube, etc. Main work in this paper is bearing capacity of the joint under bending, considering major influential parameters which include: main tube diameter (D), main tube thickness (t), length of gusset (l). The selected value of parameters in analysis are listed in Table 4.

Main tube diameter (D) effect on node bearing capacity

Bearing capacity of FEA result with t=6 mm, l=380 mm and main tube diameter which varies from 152 to 219 is shown in Figure 11. The joint bending capacity decreases with the increment of main tube diameter. Bending stiffness decrease as a result of diameter-thickness ratio increase due to t remains unchanged with D increases; stress concentrate become more significant; specimens failure in a lower load is observed when larger plastic deformation occur in connection of gusset and main tube.

Main tube thickness (t) effect on node bearing capacity

Bearing capacity of FEA result with D=168, l=380 and main tube thickness varies from 6 to 16 as shown in Figure 12. Bearing capacity increases significantly with

Table 4. Parameters value of model.

Main tube diameter (*D*/mm)	Main tube thickness (*t*/mm)	Length of gusset (*l*/mm)
152	6	340
160	7	350
164	8	360
168	10	370
170	12	380
219	16	

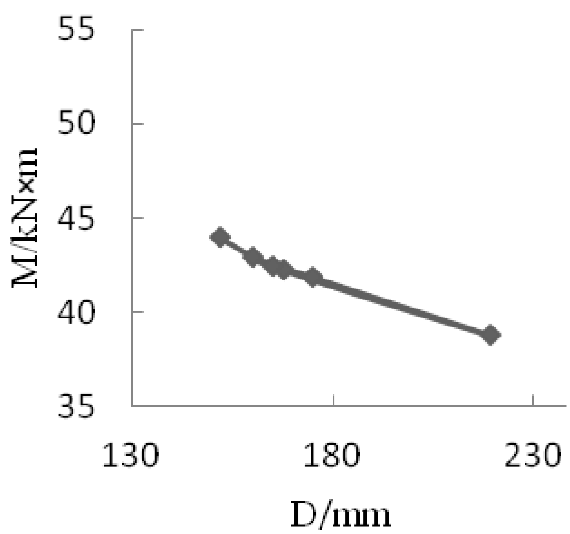


Figure 11. Variation of ultimate strength with main tube diameter.

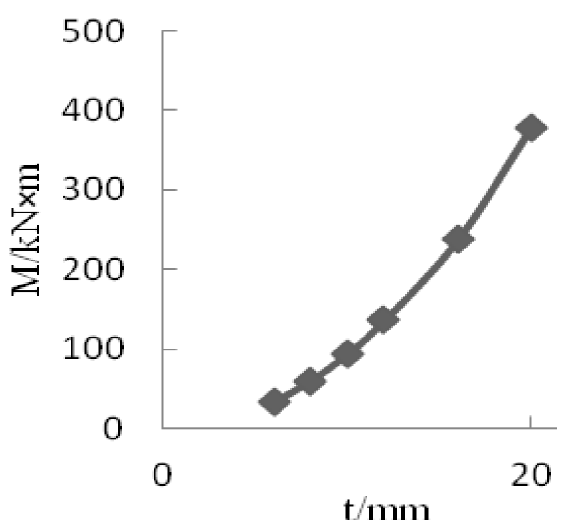


Figure 12. Variation of ultimate strength with main tube thickness.

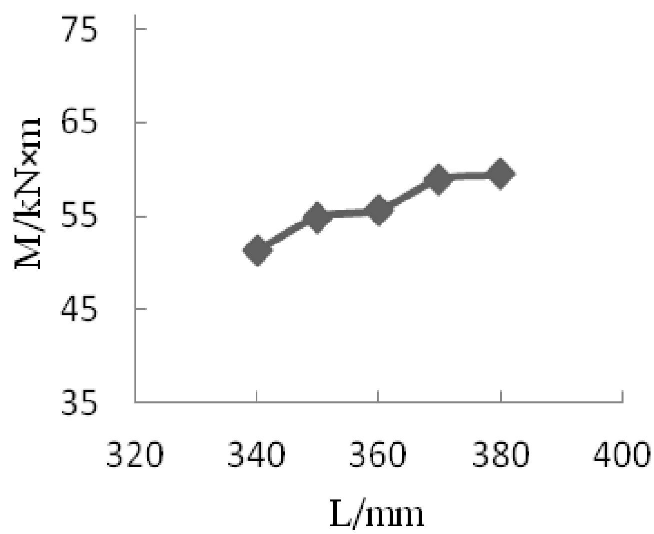


Figure 13. Variation of ultimate strength with length of gusset.

the increment of main tube thickness; curve of bearing capacity present exponential increase with the increment of main tube thickness.

Gusset length (*l*) effect on node bearing capacity

Bearing capacity of FEA result with *D*=168, *t*=8 and branch tube length varies from 340 to 380 as shown in Figure 13. Stiffness of node area increases due to the increment of gusset length; therefore, the stress in node area is distributed more uniformly and stress concentrate become smaller as a result of the increment of subjected length to load. Selected appropriate length of gusset has a great influence on node bearing capacity in real projects.

BENDING CAPACITY RECOMMENDED FORMULA OF TUBE-GUSSET K-JOINT

Recommended formula

This is based on some relevant researches of Canada (Packer and Henderson, 1992) and Japan (AIJ-SRC, 2001) in combination with the test and FEA result in this paper, and considering major influential parameters such

Table 5. Comparison between calculation formula and result of FEA and test of tube-gusset K-joint bending capacity.

Size of models (mm) [$D \times t \times L$]	Value of recommended formula (M_u / KN ×m)	Test result [M_{ut} / KN ×m]	Value of FEA [M_{ua}/ KN ×m]	(M_{ut}-M_u)/M_{ut} (%)	(M_{ua}-M_u)/M_{ua} (%)
152×6×380	27.51	30.68	28.74	10.33	4.28
168×6×380	26.51	29.37	27.15	9.73	2.36
219×6×380	24.31	24.31	25.96	10.59	10.59
168×8×380	47.14	52.36	49.47	9.96	4.70
168×10×380	73.66	80.69	76.92	8.71	4.23
168×8×340	40.59	/	42.03	/	3.42
168×8×360	43.82	/	46.27	/	5.29

as diameter and thickness of main tube and length of branch tube. Bending capacity calculation formulas of tube-gusset K-joint proposed according to sample and practical principle as follow:

$$M = A\left[1 + B\frac{l}{D}\right]t^2 l f_y \quad (1)$$

Among them, *A* and *B* are undetermined coefficients.

According to test and FEA results, fitting parameters (*D, t, l* in Table 3) and value of FEA result (*M* in Table 5) to formula (1), results in A and B; with formula (1) divided by 1.25 safety margin, then, bending capacity calculation formula of tube-gusset K-joint is attained as follow:

$$M = 5.3[1 + 0.246\frac{l}{D}]t^2 l f_y \quad (2)$$

Applicability analysis of the formula

In order to verify reliability of the formula proposed above, comparison of calculation result to results of FEA and test is shown in Table 5. Test and FEA data in Table 4 considering safety margin (1.25) due to it also considering formula (1), thus, unified the standard adopted in the process of comparison.

It can be seen in Table 5 that value of formula proposed above is closed, but a little smaller to result of FEA and test, which shows that formula (2) well reflects bending capacity of K-joint, and emphasis on safety. Recommend calculation formula has been adopted (Zhang, 2013) to contrast with FEA result of tube-gusset K-joint models (*D*=150 mm ~ 400 mm, *t*=6 mm ~ 40 mm, *l*=250 mm ~ 800 mm); the error is controlled within 5%; the applicability and reliability are verified again.

Conclusions

(1) FEA and test results show that the node bending capacity decreases with the increment of main tube diameter and increases exponentially with the increment of main tube thickness. To increase the thickness of main tube is a good means to improve capacity of this joint in reality. The article recommend ratio of D/t within 16 to 25 is reasonable, satisfy members lighter and not easily result in local bulking.

(2) The influence of gusset length to joint bending capacity is linear, and the impact on bearing capacity is small compared to other factors, simply making the length of gusset satisfying branch tube layout enough.

(3) Bending capacity of tube-gusset K-joint calculation formula proposed in this paper with universal applicability which can be used in strength-checking calculation in designing.

Conflict of Interests

The author(s) have not declared any conflict of interests.

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