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# Experimental and numerical studies on a new type of bolt-ball joint for spatial grid structures

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**ABSTRACT:** The insufficient tightening due to workmanship and bolt loosen during the life cycle of spatial structures are common safety hazards in the installation process and the use stage of spatial structures. To tackle these problems, in this paper, a new type of bolt-ball joint with octagonal high-strength bolt is developed for conventional spatial structures. For this new type of node, the force was transmitted through the contact between the high-strength bolt and the inner wall of the octagonal sleeve, and the bolt is screwed into the bolt ball to avoid the shear forces on the pins. After installation, by checking whether the tail of the pin is flush with the outer surface of the sleeve, it will be easy to judge whether the high-strength bolt is properly tightened. To investigate the behavior of this new type of nodes, an experimental study on the tensile performance of octagonal high-strength bolts was performed. It is found that, the tensile strength of the octagonal high-strength bolts for this new type meets the requirements of the Chinese specification. Further detailed experimental studies and numerical simulations were carried out to investigate other nodes, namely steel-pipe, cone head/sealing plate nodes. The results show that the stress distribution and dimensions of the whole joints and the bearing capacity of the cone head are similar between the two nodes. The compressive test of the proposed new type of sleeve is also carried out, and the results show that the failure load is more than 3 times the required design value. Finally, the torsion bearing capacity test of this new type of node is carried out. The results show that the torsional bearing capacity of the new nodes during installation is much greater than that of the traditional ones.

**Keywords:** bolt-ball joint, "insufficient tightening", octagonal high-strength bolts, experimental study, failure modes, numerical simulation

## 1. Introduction

The large-span spatial structure has been developed rapidly in the past few decades. Among them, space grid, latticed shells, etc., are the most widely used structural forms. Nodes are an essential part of single-layer grid structures. At present, more than 100 node systems have been developed in single-layer grid structures across the world [1]. Among which MERO node[2] (Fig.1), invented by Dr. Max Mengerhausen of MERO Company in Germany in 1942, is the most famous and widely used one. Others, such as Space Deck (UK), Unistrut (US), Ohbayashi System (Japan), Unibat (France), Triodetic (Canada), and NODUS (UK), have also been promoted [3].

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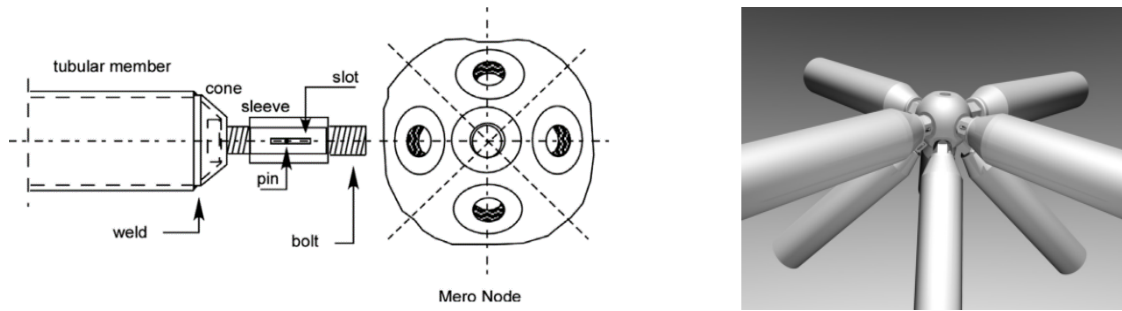


Fig.1. MERO joint.

33 In China, the bolt-ball joint was introduced from MERO in Germany in the 1970s. After decades of  
 34 development, the joint form (Fig.2) has been formed. It has been widely used in industrial plants, stadiums,  
 35 transportation hubs, terminals, and other large roof structures [4].

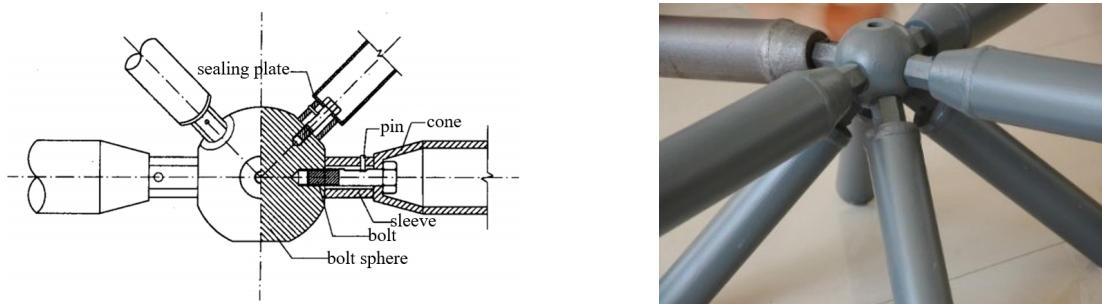
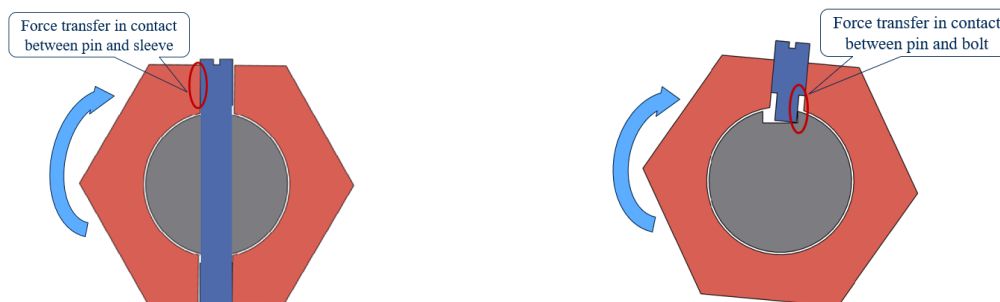


Fig.2. Traditional Chinese bolt-ball joint.

36 Traditional Chinese bolt-ball joints resemble MERO joints. Both bolts are driven by shear force of the pins to  
 37 rotate and therefore screw into the sphere [5]. The difference is that the MERO joint has pin holes on the bolts  
 38 and a sliding groove on the sleeve. During installation, the sleeve is inserted into the bolt, and the pin is inserted  
 39 from the chute of the sleeve and screwed into the pin hole of the high-strength bolt. The rotating sleeve transmits  
 40 the torsional force through the contact between the pin and the wall of the sleeve chute (Fig.3a), driving the bolt  
 41 into the sphere until the sleeve and the surface of the bolt ball are top-tight. At this time, the pin is at the bottom  
 42 of the sleeve sliding groove. By observing the state of the pin through the sliding groove, it can determine whether  
 43 the pin is cut in the process of screwing. By observing the position of the pin in the sliding groove, it can determine  
 44 the length of the bolt screwed into the ball. In the traditional Chinese bolt-ball joints [6], only pin holes are set  
 45 on the sleeve, and sliding grooves (including deep and shallow grooves) are made on the bolts. During installation,  
 46 the sleeve is inserted into the bolt, and the pin is screwed into the screw hole of the sleeve until the top end is  
 47 pushed into the shallow groove of the bolt. Rotating the sleeve can transmit torque through the contact between  
 48 the pin and the bolt chute wall (Fig.3b), driving the bolt to rotate together, and the bolt can be screwed into the  
 49 sphere. When the sleeve and the bolt ball are tightened, the pin should reach the deep groove of the bolt. Rotate  
 50 the pin again until the top end of the pin is pushed into the deep groove of the bolt.



(a) MERO joint

(b) Traditional Chinese bolt-ball joint

Fig.3. Screwing mechanism of high-strength bolt into sphere

51 In the traditional Chinese bolt-ball joints, when the pin is in the shallow groove of the bolt, the exposed length  
52 of the pin tail is obvious (Fig.4a). However, due to the small difference between the depth of the deep groove and  
53 the shallow groove of the traditional high-strength bolt, when the pin is rotated into the deep groove, the pin tail  
54 is still exposed, and the exposed length changes little (Fig.4b), making it impossible to judge whether the high-  
55 strength bolt is fully screwed into the bolt sphere. Even if the depth difference between the deep groove and  
56 shallow groove of the high-strength bolt is increased, the pin may have been shear off. Therefore, it is still  
57 impossible to accurately determine whether the depth of the high-strength bolt into the bolt sphere is sufficient  
58 simply based on the exposed length of the pin tail. It is impossible to judge the shear state of the pin and the  
59 screw length of the bolt screwed into the sphere through observation in the entire installation process.



(a) Pin in shallow groove



(b) Pin in deep groove

Fig.4. Pin in shallow/deep groove status

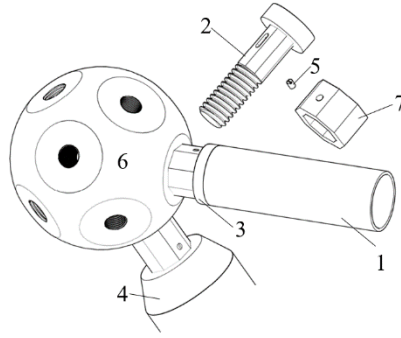
60 At the construction sites, during the assembling of the space structure, construction workers often need to  
61 work on scaffolding high above-ground. However, due to the assembly error of each component, the axis of the  
62 bolt and the corresponding bolt sphere screw hole is not completely coincided, and there is a small amount of  
63 deviation. During the installation process, the installation member will be affected by its weight and the members  
64 that have been installed. The process of screwing the bolt into the bolt sphere is carried out under the condition  
65 of tension (compression) of the bolt. In the process of screwing the bolt into the bolt sphere, it is necessary to  
66 overcome the friction between the high-strength bolt thread and the inner thread of the bolt sphere. Therefore,  
67 the worker needs to use a large torque to screw the bolt into the bolt sphere. When the pin is subjected to excessive  
68 shear force, it will be sheared off, which will cause the high-strength bolt to be insufficiently screwed into the  
69 bolt sphere and “insufficient tightening” will occur, as shown in Fig.5. During the service period, “insufficient  
70 tightened high-strength bolts cannot effectively bear the tension due to the insufficient depth of the bolt screwed  
71 into sphere, and it is easy to be pulled out. This is one of the key safety hazards and accidents inducements  
72 commonly existing in the grid structure of the bolt-ball joint. Several engineering accidents are directly related  
73 to the "insufficient tightening" phenomenon of high-strength bolts. In a space grid project in Tianjin City, due to  
74 the insufficient screwing depth of a bolt, one of the web members was loosened, which induced the collapse of  
75 the structure [7]. In the lecture hall of a medical college in Shanxi province, due to the fracture of a pin, the sleeve  
76 can rotate freely, and there is a large gap between the sleeve and the bolt sphere, which causes the collapse of the  
77 grid [8]. In Inner Mongolia Xin Feng Power Plant 1# steam turbine room, a space grid did not meet the  
78 requirement of Chinese code due to inadequate tightening of some high-strength bolts [9] and there were large  
79 gaps (2~25mm) between some bolts and sleeves [10], resulting in collapse. To tackle the "insufficient tightening"  
80 issues, this paper presents a new anti-insufficient tightening bolt-ball joint for spatial grids (Fig.6). By designing  
81 the form and size of bolts, sleeves, cones/sealing plates and pins, the screwing mechanism of the bolts is changed.  
82 After installation, the depth of the high-strength bolt screwed into the sphere can be determined only by directly

83 inspection the exposed length of the pin tail.



84  
85

Fig.5. The insufficient tightening of the bolt-sphere joints of grid structures.



86  
87

Fig.6. Visual anti-insufficient tightening bolt-ball joint for spatial grid structure[11].

## 88 2. New bolt-ball joint design

### 89 2.1 The composition and innovation of new bolt-ball joint

90 The new bolt-ball joint (Fig. 6) consists of bolt sphere (denoted as 6), high-strength bolt (denoted as 2), sleeve  
91 (denoted as 7), cone head (denoted as 4)/ sealing plate (denoted as 3), pin (denoted as 5) and other accessories.  
92 The force transfer path is consistent with the traditional bolt-ball joint. When members in spatial grids are  
93 subjected to tension, the load path is as follows: tensile force → steel pipe → cone head/sealing plate → bolt  
94 → bolt sphere. When members are subjected to compression, the load path is as follows: pressure force → steel  
95 pipe → cone head/sealing plate → sleeve → bolt sphere [12].

96 Compared with the traditional bolt-ball joint, the main innovations of the proposed new bolt-ball joint are as  
97 follows :(1) The mechanism of the high-strength bolts screwing into the bolt sphere is different. In the new bolt-  
98 ball joint (Fig.7), the cross-section of the shank of the bolt is adapted into polygonal shape rather than the  
99 traditional circular shape, the movement of the bolts relies on rotating the sleeve so that the polygonal shank of  
100 the high-strength bolt is in contact with the inner wall of the sleeve (also made in polygonal shape) to transfer  
101 torque and screw the bolt into the sphere. In this process, the pin and the bolt chute will not contact each other.  
102 Therefore, the pin is not stressed. (2) After the assembly of the new bolt-ball joint, the screwing depth of the high-  
103 strength bolt can be judged by inspection of the exposed length of the pin tail. When the pin is located in the  
104 shallow groove of the bolt, the exposed length of the tail is apparent (Fig.8a). When the pin is screwed into the  
105 deep hole of the bolt, its tail is flush with the sleeve surface and not exposed (Fig.8b), indicating that the high-  
106 strength bolt is completely screwed into the ball.

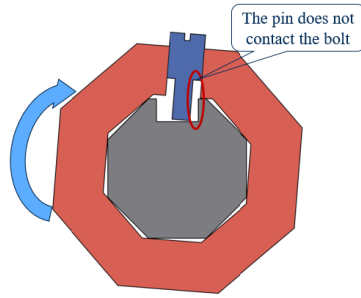
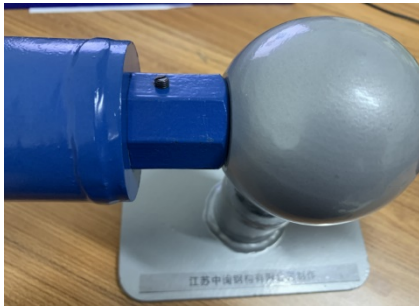


Fig.7. Screwing mechanism of high-strength bolt into sphere



(a) Pin in shallow groove



(b) Pin in deep hole

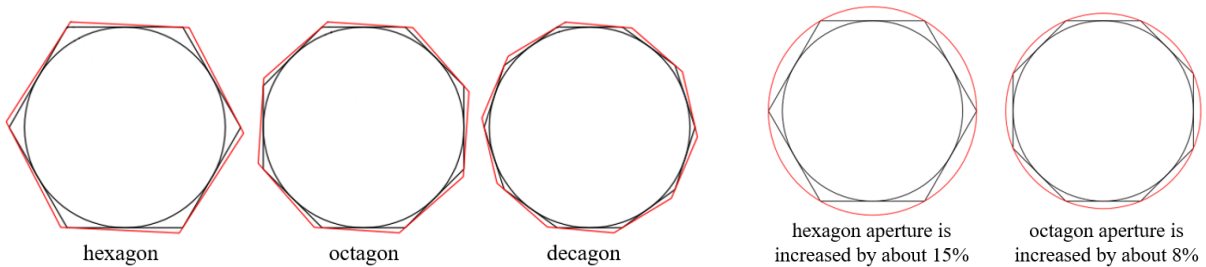
Fig.8. Pin in shallow/deep groove (hole) status of the new joint

107 **2.2 Design of high-strength bolts**

108 **2.2.1 Determination of polygon edge numbers of high-strength bolts**

109 The polygon segment of the high-strength bolt is determined based on the same inscribed circle with a nominal  
 110 diameter of the thread segment. The number of sides of the regular polygon is preliminarily designed as 6, 8,  
 111 and 10, as shown in Fig.9a. Because the shape of decagon is the most complicated, the workmanship of the size of  
 112 the bolt and the sleeve are the highest, and the size errors can easily lead to slippage between decagonal bolts and  
 113 sleeves during rotation. Therefore, the decagon is not used in the proposed new joints.

114 For the same type of high-strength bolt, the hexagonal and octagonal segment and their inscribed circles and  
 115 circumscribed circles are shown in Figure 8b, where both the inscribed circle diameters are the same as the  
 116 nominal diameter of the bolt thread segment. The aperture of the circumcircle of the hexagon is enlarged by about  
 117 15% compared with the nominal diameter of the bolt, while that of the octagon is only 8%. After the bolt is put  
 118 into the cone head, the contact surface of different types of bolts nuts and the cone plate is shown in Fig.9c-e.  
 119 The contact area reduction table is shown in Table 1. It can be concluded that the hexagon bolt contact surface  
 120 reduction rate is about 2 times that of the octagonal bolt contact surface reduction rate. The contact area between  
 121 the bolt and the cone head/sealing plate is too small, thus reducing the tensile bearing capacity of the conical  
 122 head/sealing plate. Therefore, the octagon is chosen as the polygon section of the high-strength bolt.



(a) Comparison of different polygon sides

(b) Hexagonal and octagonal segments

123  
124

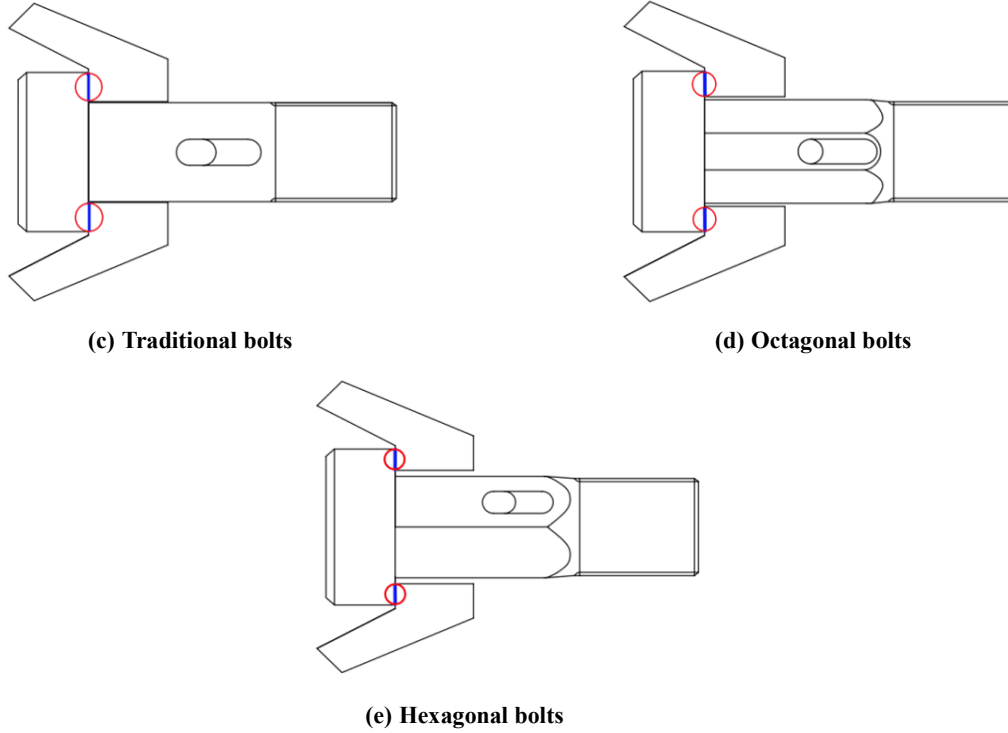


Fig.9. Contact surface of different bolt nuts and cone heads

Table 1

Contact area reduction table for different types of bolts and cone head.

Cone head type	Contact area of traditional bolts/cone head (mm <sup>2</sup> )	Contact area of hexagon bolts/cone head (mm <sup>2</sup> )	Area reduction rate (%)	Contact area of octagonal bolts/cone head (mm <sup>2</sup> )	Area reduction rate (%)
ZT75.5-3.75-20	360.315	254.34	-29.41	309.09	-14.22
ZT114-4-36	1299.96	956.72	-26.40	1118.63	-13.95
ZT159-6-45	2185.44	1641.44	-24.89	1923.05	-12.01
ZT168-8-56	3808.035	2990.65	-21.46	3389.43	-10.99

### 2.2.2 Design of the bolts

The form of the octagonal high-strength bolt is shown in Fig.10.

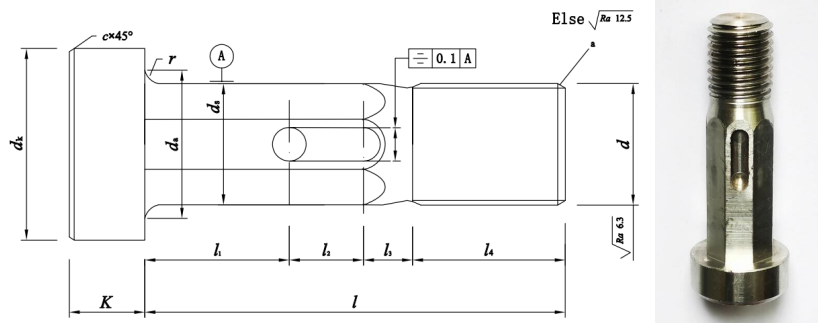
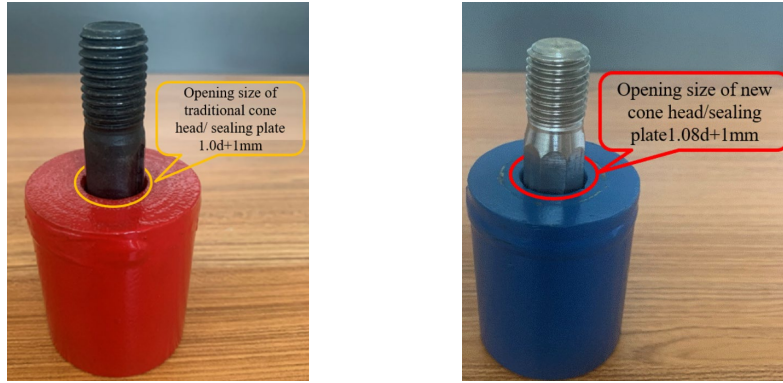


Fig.10. Octagonal high-strength bolt

Where  $K$  is the nut thickness;  $d_k$  is the diameter of the nut;  $d_a$  is the length between the bolt member and the nut chamfer;  $d_s$  is the length of the opposite side of the octagon screw;  $d$  is the diameter of the bolt;  $l_1$  is the length from the bottom of the nut to the center of the deep hole;  $l_2$  is the length of the chute;  $l_3$  is the transition length between octagonal screw and thread segment;  $l_4$  is the length of the thread segment.

140 **2.3 Cone head/sealing plate design**

141 The form of cone head/sealing plate of the new joint is the same as that of the traditional joint. The hole  
 142 diameter of the traditional cone head/sealing plate is 1mm larger than the nominal diameter of the corresponding  
 143 bolt (Fig.11a). When the octagonal bolt of the same nominal thread diameter is used, the traditional hole can no  
 144 longer accommodate the octagonal high-strength bolts. Therefore, it is necessary to increase the size of opening  
 145 circular hole diameter of the cone head/sealing plate to adapt to the octagonal high-strength bolt (Fig.11b).



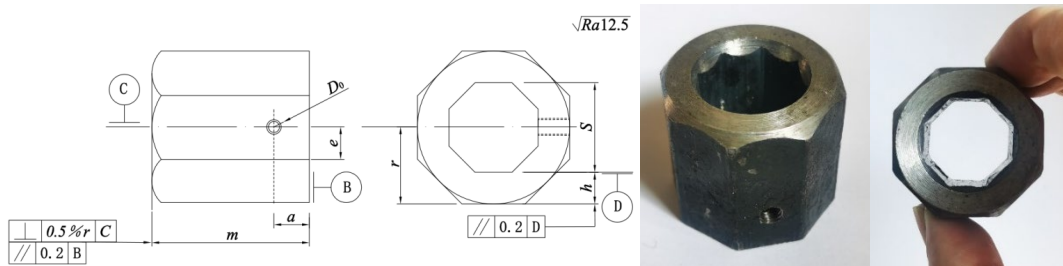
146 (a) Traditional joints

147 (b) New joints

148 **Fig.11. Opening circular holes of cone head/sealing plate**

149 **2.4 Sleeve**

150 The design principles of the sleeve are as follows: (1) The distance between the opposite sides of the octagon  
 151 in the sleeve section is 1mm or 0.5mm (MY20 and below) larger than the distance between the opposite sides of  
 152 the octagon section of the high-strength bolt. (2) Sleeve wall thickness  $h$  (Fig.12) is mainly determined from the  
 153 following three aspects: 1) Bearing capacity is equivalent to the corresponding traditional sleeve bearing capacity.  
 154 2) The high-strength bolt is tightened, and the pin is flush with the sleeve. 3) The types of pins should not be too  
 155 many. The sectional view of the sleeve is shown in Fig.11.



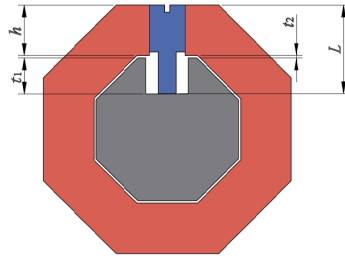
156 **Fig.12. Sleeve.**

157 Where  $m$  is the total length of the sleeve;  $D_0$  is the pin aperture;  $e$  is the distance from the center of the pin hole  
 158 to the edge of the outer octagon;  $S$  is the distance between the opposite sides of the octagon in the sleeve;  $a$  is the  
 159 distance from the center of the pin hole to the end of the sleeve.

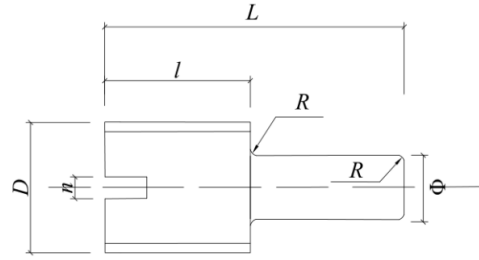
160 **2.5 Pin**

161 The total length  $L$  of the pin is determined by Fig.13a and formula (1) below. The form of the pin is shown in  
 162 Fig.13b.

163 
$$L = h + t_1 + t_2 \tag{1}$$



(a) End screw position of pin



(b) Pin detail

Fig.13. Pin.

165 Where  $D$  is the diameter of the pin end;  $l$  is the length of the pin thread section;  $\Phi$  is the diameter of the pin  
 166 head.

### 167 3. Experimental study on tensile strength of octagonal high-strength

#### 168 bolts

169 "High strength bolts for joints of space grid structures" in Chinese (GB/T 16949-2016) require that high-  
 170 strength bolts should be screwed into the internal threads of a special anchor in a tensile test so that the length of  
 171 the screw is not less than  $6P$  (Where  $P$  is the distance between a point on a screw thread and the corresponding  
 172 point on the adjacent screw thread, and the screw length not less than  $6P$  is the actual use of the simulated bolt).  
 173 The length of unscrewed thread is not less than  $2P$ . A wedge is placed under the bolt head. When the test tension  
 174 reaches the specified range, the bolt shall break at the threaded part of the junction between the thread and the  
 175 screw [13].

#### 176 3.1 Materials, dimensions, and loading equipment for octagonal high-strength bolts

177 Four commonly used types of octagonal high-strength bolts were designed: MY20, MY36, MY45, and MY56.  
 178 A total of 12 samples were prepared for 3 samples of each type. The materials and dimensions of octagonal high-  
 179 strength bolts are shown in Table 2.

180 Using 100t hydraulic tensile testing machine (Fig.14b) for MY20, MY36 high-strength bolts tensile load test.  
 181 Using 300t horizontal tensile testing machine (Fig.14a) for MY45, MY56 high-strength bolts tensile load test.  
 182 Screw the specimen into a special fixture (Fig.14c) and load it on the test machine (Fig.14d).

183 **Table 2**

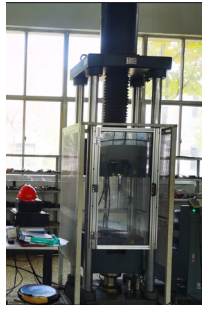
184 Materials and dimensions of octagonal high-strength bolts.

Bolt	Strength grade	Material	$l$ (mm)	$d_k$ (mm)	$d$ (mm)	$K$ (mm)
MY20	10.9S	40Cr	73	31	20	12.5
MY36	10.9S	40Cr	125	57	36	22.5
MY45	9.8S	40Cr	145	72	45	28
MY56	9.8S	40Cr	172	92	56	35



185

(a) 300t horizontal tensile testing machine



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(b) 100t hydraulic tensile testing machine

(c) Anchor

(d) Sample loading

Fig.14. Test equipment.

### 190 3.2 Experimental result

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When the octagonal high-strength bolt reaches the ultimate tensile strength, the bolt fracture failure occurs as shown in Fig.15, and the load-displacement curve is shown in Fig.16. The fracture of MY20 extends in the direction of 60° at the junction of thread and screw (Fig.15a), and the other three groups are all fractured at the junction of thread and screw. The fracture surface is smooth (Fig.15b-d), which is the same as the fracture location and shape of high-strength bolt tests in other documents [14]. According to the test results in Table 3: Except for the tensile load of one sample in MY45, which exceeds 2.36% of the maximum tensile load specified in the standard, the failure load, failure position, failure form, and elongation of the other octagonal high-strength bolts all meet the requirements of the current standard "High strength bolts for joints of space grid structures" in Chinese (GB/T 16949-2016) [13]. Therefore, the tensile capacity of octagonal high-strength bolts meets the requirements.



(a) MY20



(b) MY36



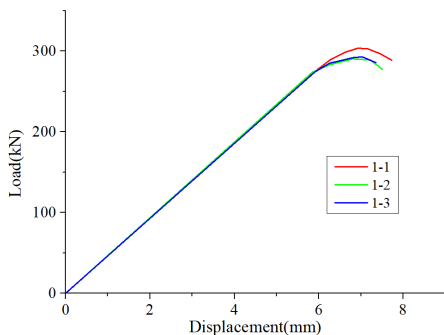
(c) MY45



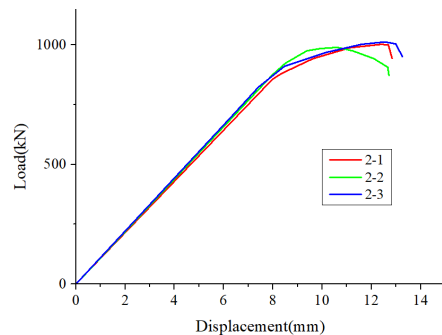
(d) MY56

Fig.15. Failure mode.

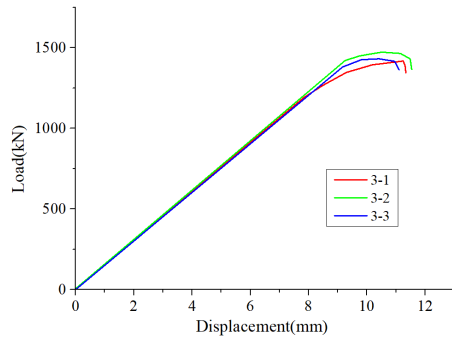
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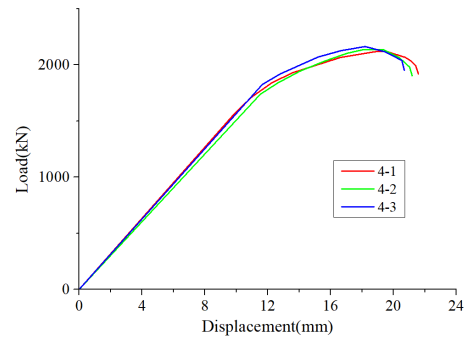
(a) MY20



(b) MY36



(c) MY45



(d) MY56

Fig.16. The load-displacement curve of the bolt.

202 **Table 3**  
 203 Experimental results.

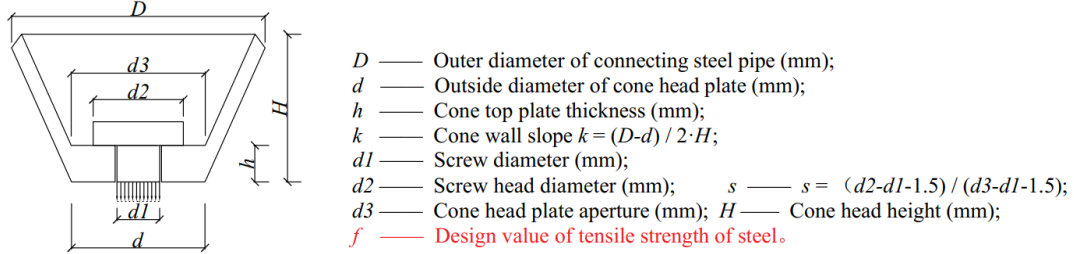
Bolt	Number	Tensile load (kN)	The code requires the tensile load range (kN)	Failure location and failure form	Elongation (%)	The specification requires elongation (%)	Meets specification requirements (T/F)
MY20	1-1	302	255~304	The joint between the thread and the screw is extended and fractured in the direction of 60°	11.84	≥10	T
	1-2	290			12.87		T
	1-3	291			10.16		T
MY36	2-1	1003	850~1013	Smooth fracture at the junction of thread and screw	10.48	≥10	T
	2-2	991			10.46		T
	2-3	1011			10.86		T
MY45	3-1	1408	1179~1441	Smooth fracture at the junction of thread and screw	10.31	≥10	T
	3-2	1475			10.38		Tensile load beyond the normal tensile range
	3-3	1422			10.15		T
MY56	4-1	2128	1930~2358	Smooth fracture at the junction of thread and screw	12.62	≥10	T
	4-2	2152			13.96		T
	4-3	2163			12.50		T

## 204 4. Bearing capacity of cone head

205 Under different stress conditions, the bolt-ball joint has different force transmission paths and acting parts.  
 206 When the member is under pressure, the pressure between the sleeve and the cone head is transmitted along with  
 207 the cone shell, which is equivalent to the cone shell bearing the in-plane pressure. When the member is under  
 208 tension, the tensile force between the bolt and the cone head is transferred by the nut and the cone head top plate,  
 209 and the cone head top plate is subjected to the out-of-plane force. For shell-plate structure, the in-plane strength  
 210 of the shell is higher than the out-of-plane strength of the plate. Therefore, the bearing capacity of the cone head  
 211 is higher under compression than under tension. The cone head plate in the new bolt ball joint has to meet the  
 212 requirements of octagonal high-strength bolts, which increases the hole diameter (Fig.11b). As the size of the  
 213 cone head has changed, it is necessary to study the bearing capacity of the cone head.

214 Zhang et al. [15] studied the theoretical analysis and simplified calculation of the strength of the cone head  
 215 (Fig.17). The obtained the approximate formula (2) for calculating the tensile design bearing capacity of the cone  
 216 head:

$$217 [N]=0.4487 \cdot (D)^{1.73534} \cdot (k)^{-0.399} \cdot (h/H)^{0.6926} \cdot (s)^{0.26034} \cdot f \quad (2)$$



219 **Fig.17.** Schematic of cone head calculation.

220 Where:  $88.5\text{mm} \leq D \leq 275\text{mm}$ ,  $0.15 \leq d1/D \leq 0.4$ ,  $0.5 \leq d/D \leq 0.7$ ,  $0.2 \leq k$ ,  $h/H \leq 0.5$ ,  $0.25 \leq s \leq 1.0$ ,  $N$  unit is  
 221 Newton (N).

222 Based on this formula, it can be seen that the relationship between the tensile design bearing capacity of the  
 223 cone head  $N$  and the parameter  $s$  is positively correlated. Therefore, take the screw diameter  $d1$  as the independent  
 224 variable and  $s$  as the dependent variable, and take the derivative of  $s$ , as shown in formula (3).

$$225 \frac{ds}{d(d1)} = \left( \frac{d2-d1-1.5}{d3-d1-1.5} \right)' = \frac{(-1) \cdot (d3-d1-1.5) - (-1) \cdot (d2-d1-1.5)}{(d3-d1-1.5)^2} = \frac{d2-d3}{(d3-d1-1.5)^2} < 0 \quad (3)$$

226 The derivative result is negative, indicating that the screw diameter  $d1$  is negatively correlated with  $s$ . Which  
 227 is the screw diameter  $d1$  is negatively correlated with the tensile design bearing capacity of the cone head.  
 228 Therefore, the increase of screw diameter  $d1$  is unfavorable to the tensile design bearing capacity of the cone  
 229 head. The outer diameter of the connecting steel pipe  $D$ , the thickness of the top plate  $h$ , and the diameter of the  
 230 screw head  $d2$  are positively correlated with the tensile design bearing capacity of the cone head. In order not to  
 231 increase the cost, the manufacturing mold of the cone head is not changed, only the opening size of the cone head  
 232 is changed. In the design of high-strength bolts with new bolt-ball joints, by increasing the diameter  $d2$  of the  
 233 screw head, the problem of the reduced tensile design bearing capacity of the cone head due to the increase of  
 234 the screw diameter  $d1$  is solved.

235 Expand the screw head diameter of MY16~MY30 bolts by 1mm, and expand the screw head diameter of  
 236 MY36~MY85 bolts by 2mm. According to the order of bolt models from small to large, 9 kinds of matching cone  
 237 heads made of Q235 are selected, according to formula (2), carrying out the calculation of the tensile design  
 238 bearing capacity of the cone head. The calculation results are shown in Table 4. In addition to the taper head  
 239 model ZT89-4-20 tensile design bearing capacity decreased, the other models are slightly improved. It shows  
 240 that increasing the diameter  $d2$  of the screw head by a certain range can slightly increase the bearing capacity of  
 241 the cone head, offsetting the reduction of the tensile design bearing capacity due to the enlargement of the cone  
 242 head opening hole.

243 **Table 4**

244 Comparison of tensile design bearing capacity of cone head before and after reaming.

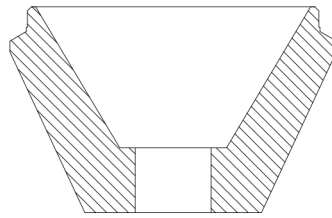
Steel material	Cone head type	Change in diameter of cone head after reaming (mm)	Hole expansion rate (%)	Length of original screw head	Length of expansion head diameter	Original tensile strength (kN)	Tensile strength after reaming	increasing rate (%)
Q235B	ZT89-4-20	1.5	7.14	30	31	158.47	156.46	-1.27

Q235B	ZT108-4-27	2	7.14	41	42	210.21	210.58	0.17
Q235B	ZT140-4.5-30	2.5	8.06	46	49	306.92	307.67	0.24
Q235B	ZT159-6-36	3	8.1	55	57	418.98	428.32	2.23
Q235B	ZT168-8-42	3.5	8.14	65	67	504.14	513.36	1.83
Q235B	ZT180-8-42	3.5	8.14	65	67	581.52	592.15	1.83
Q235B	ZT194-10-56	4.5	7.9	90	92	742.86	752.84	1.34
Q235B	ZT219-8-48	4	8.16	75	77	681.24	691.81	1.55
Q235B	ZT245-10-64	5.5	8.46	100	102	963.35	975.364	1.25

245 Note: The cone head model ZT89-4-20 means that the diameter of the cone head connecting steel pipe is 89mm, the thickness is  
246 4mm, and the matching bolt model is M20.

## 247 5. Steel pipe - Cone head /sealing plate and bolt integral test

248 The slope  $k$  of the cone wall of the cone head in the theoretical calculation of the tensile design bearing capacity  
249 of the cone head is a fixed value, assuming that the cone wall of the cone head is of equal thickness. Fig.18 shows  
250 the cone head used in real construction projects. The slope  $k$  of the inner cone head wall and the outer cone head  
251 wall of the cone head are different. The cone head wall is not of equal thickness, and the thickness of the cone  
252 head wall increases from the junction with the pipe to the top plate of the cone head. Therefore, only using the  
253 theoretical formula (2) to analyze the tensile design bearing capacity of the cone is deviated. It is necessary to  
254 carry out the overall test of the steel pipe-cone head/sealing plate and bolts to further analyze the influence of the  
255 increase in the size of the cone head opening and the increase in the diameter of the screw head on the tensile  
256 bearing capacity of the cone head and the overall test piece.



257  
258 **Fig.18.** Cone head used in real construction projects

259 In the test, the bolt type selected is commonly used in actual projects and the corresponding member. The  
260 elastic stiffness, failure mode, and failure load of the new bolt-ball joint and the traditional bolt-ball joint were  
261 compared by selecting typical bolts from each type of bolt by setting a control test. The bolt type, steel pipe type,  
262 size, and material selected in the test are shown in Table 5. Fig.19 is the schematic diagram of test loading, and  
263 Fig.20 is the loading device.

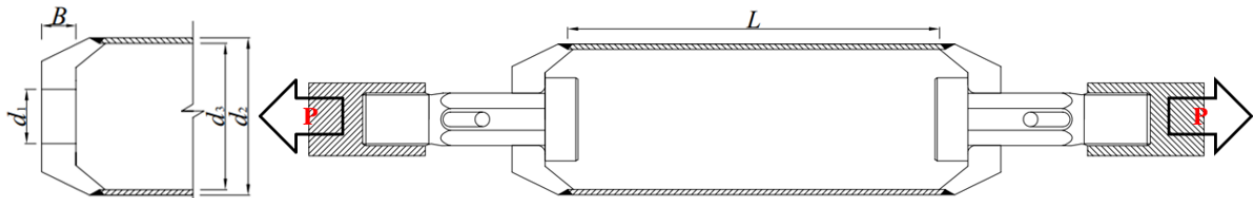
264 **Table 5**

265 Type of bolt, type of steel pipe, size, and material.

Bolt	Strength grade	Bar type	Materials	$d$ (mm)	$B$ (mm)	$d_1$ (mm)	$d_2$ (mm)	$d_3$ (mm)	$L$ (mm)
M20	10.9S	$\Phi 60 \times 3.5$	Q355	20	18	21	60	53	250
		$\Phi 75.5 \times 3.75$	Q355				75.5	68	
MY20	10.9S	$\Phi 60 \times 3.5$	Q355	20	18	21.5	60	53	250
		$\Phi 75.5 \times 3.75$	Q355				75.5	68	
M36	10.9S	$\Phi 114 \times 4$	Q235	36	30	37	114	106	

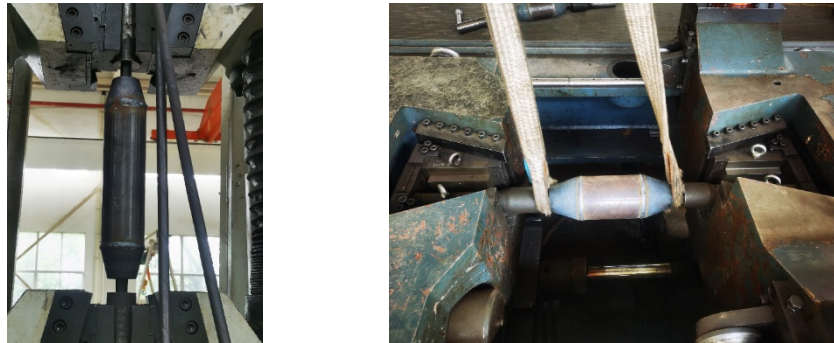
		$\Phi 114 \times 4$	Q355			114	106	
		$\Phi 140 \times 4.5$	Q235			140	131	
MY36	10.9S	$\Phi 114 \times 4$	Q235	30	40	114	106	
		$\Phi 114 \times 4$	Q355			114	106	
		$\Phi 140 \times 4.5$	Q235			140	131	
		$\Phi 159 \times 6$	Q235			159	147	
M45	9.8S	$\Phi 159 \times 6$	Q235		46	159	147	
MY45	9.8S	$\Phi 159 \times 6$	Q235	45	36	159	147	
		$\Phi 159 \times 8$	Q235			49.5	159	147
		$\Phi 159 \times 10$	Q235			159	139	
M56	9.8S	$\Phi 180 \times 12$	Q235		57	180	156	
MY56	9.8S	$\Phi 159 \times 8$	Q355	56	45	61.5	159	151
		$\Phi 180 \times 12$	Q235			180	156	

266 Note: The type of member is  $\Phi A \times B$ , where  $\Phi A$  represents the diameter of the member and  $B$  represents the thickness of the steel  
267 pipe.



268  
269

Fig.19. Test loading instructions.



270  
271  
272

(a) 100t hydraulic tensile testing machine (b) 300t horizontal tensile testing machine

Fig.20. Loading device.

273 The depth of high-strength bolt screw-in fixture meets the requirements of "Technical specification for space  
274 frame structure" in Chinese (JGJ7-2010) [8] of 1.1 times bolt diameter  $d$ . There are 26 new bolt-ball joint  
275 specimens and 13 traditional bolt-ball joint specimens, a total of 39 specimens. Fig.21 shows the three failure  
276 modes of specimens: (1) Steel pipe failure: When the steel pipe reaches the ultimate tensile strength, the steel  
277 pipe is broken from the middle part, and there is an obvious necking phenomenon. Before the fracture, there is a  
278 "thumping" sound, and when it breaks, it makes a "pop" sound. (2) Bolt failure: The high-strength bolt reaches  
279 the ultimate tensile strength, and the failure position is at the junction of the screw and the threaded section. There  
280 is no apparent necking phenomenon. It is consistent with the previous literature [16-17], and it makes a huge  
281 noise when it fails. (3) Weld failure: Two of the 39 specimens fractured from the weld, but the failure load was  
282 also within the calculated failure load range of the member, indicating that the quality of the weld between the

283 steel pipe and the cone satisfied the "Standard for construction quality of steel structure" in Chinese (GB 50205-  
 284 2020) [18] and other strength connection requirements. There was no failure of cone head/sealing plate in all test  
 285 schemes, and the failure position and load of each specimen were shown in Table 6. Fig.22 shows the failure of  
 286 the specimen with new joints, and Fig.23 shows the load-displacement curve of the specimen.



(a) Steel pipe damage (MY36  $\Phi 114 \times 4-1$ ) (b) Bolt damage (MY56  $\Phi 180 \times 12-1$ ) (c) Weld damage (MY45  $\Phi 159 \times 6-2$ )

Fig.21. Failure mode.

287 **Table 6**  
 288 Failure mode.

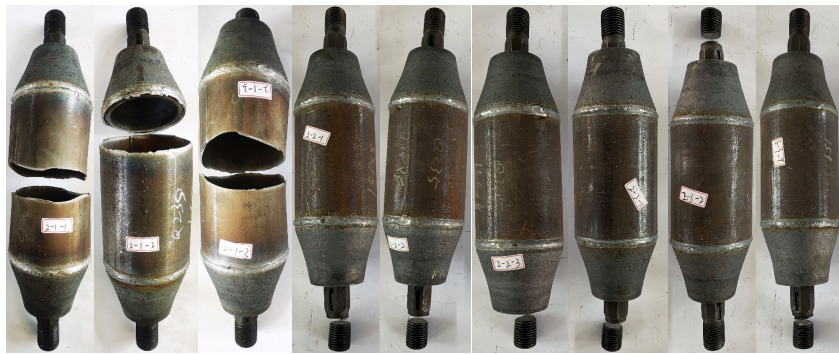
Bolt	Bar type	Number	Materials	Damage location	Failure control components/ specification require tension load range (kN)	Tensile load (kN)
MY20	$\Phi 60 \times 3.5$	1	Q355	Bolt	Bolt /255~304	283
		2	Q355	Bolt		279
	$\Phi 75.5 \times 3.75$	1	Q355	Bolt	Bolt /255~304	282
		2	Q355	Bolt		292
		3	Q355	Bolt		289
M20	$\Phi 60 \times 3.5$	1	Q355	Bolt	Bolt /255~304	268
		2	Q355	Bolt		282
	$\Phi 75.5 \times 3.75$	1	Q355	Bolt	Bolt /255~304	267
		2	Q355	Bolt		274
		3	Q355	Bolt		288
MY36	$\Phi 114 \times 4$	1	Q235	Steel pipe	Steel pipe /518~635	593
		2	Q235	Steel pipe		570
	$\Phi 140 \times 4.5$	1	Q235	Steel pipe	Steel pipe /718~881	872
		2	Q235	Steel pipe		877
	$\Phi 159 \times 6$	1	Q235	Bolt	Bolt /850~1013	974
2		Q235	Bolt	1010		
M36	$\Phi 114 \times 4$	1	Q235	Steel pipe	Steel pipe 518~635	567
		2	Q235	Steel pipe		569
	$\Phi 114 \times 4$	1	Q355	Steel pipe	Steel pipe /677~857	759
		2	Q355	Weld		704
MY45	$\Phi 159 \times 6$	1	Q235	Steel pipe	Steel pipe /1081~1326	1315
		2	Q235	Weld		1323
		3	Q235	Steel pipe		1251
	$\Phi 159 \times 8$	1	Q235	Bolt	Bolt /1179~1441	1439
		2	Q235	Bolt		1435

		3	Q235	Bolt		1433
		1	Q235	Bolt		1426
	$\Phi 159 \times 10$	2	Q235	Bolt	Bolt /1179~1441	1432
		3	Q235	Bolt		1421
<b>M45</b>	$\Phi 159 \times 6$	1	Q235	Steel pipe	Steel pipe /1081~1326	1243
		2	Q235	Steel pipe		1211
<b>MY56</b>	$\Phi 159 \times 8$	1	Q235	Steel pipe	Steel pipe /1423~1745	1739
		2	Q235	Steel pipe		1707
	$\Phi 159 \times 8$	1	Q355	Steel pipe	Steel pipe /1857~2352	1857
		2	Q355	Steel pipe		1862
<b>M56</b>	$\Phi 180 \times 12$	1	Q235	Bolt	Bolt /1930~2358	2193
		2	Q235	Bolt		2191
	$\Phi 180 \times 12$	1	Q235	Bolt	Bolt /1930~2358	2138
		2	Q235	Bolt		2241



(a) MY20

(b) MY36



(c) MY45



(d) MY56

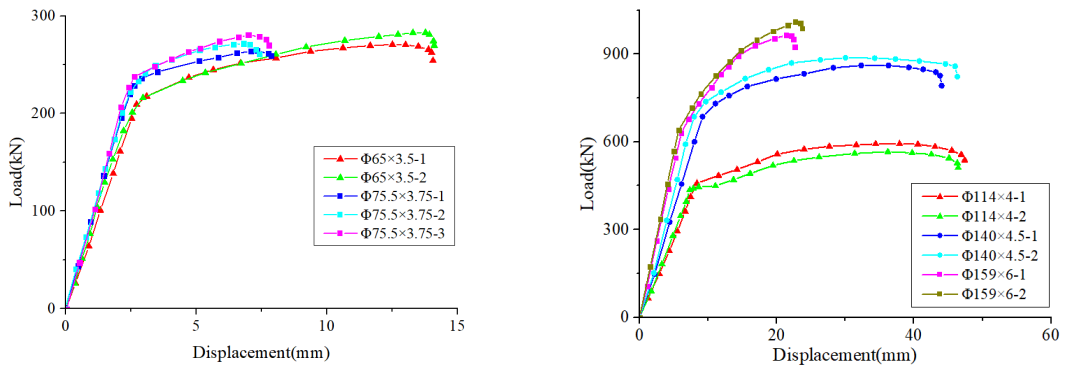
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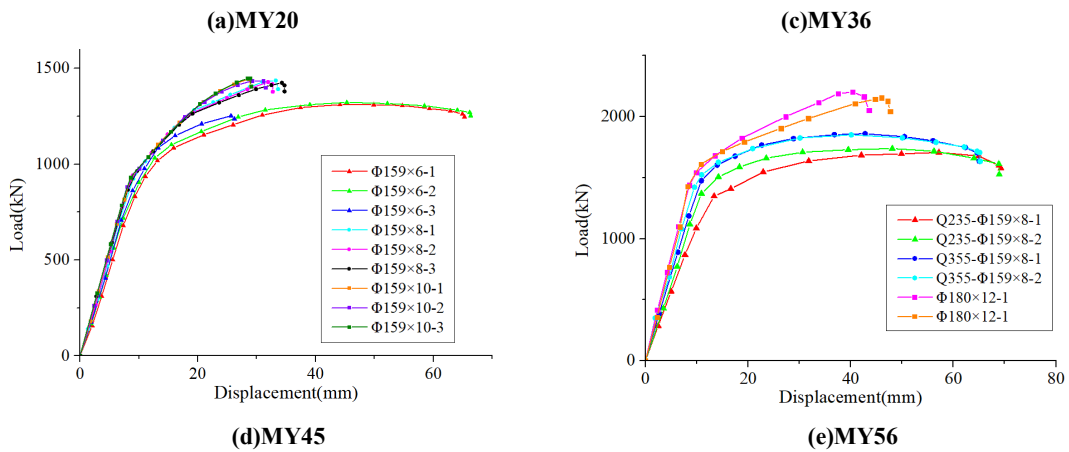
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Fig.22. Failure diagram of each specimen.



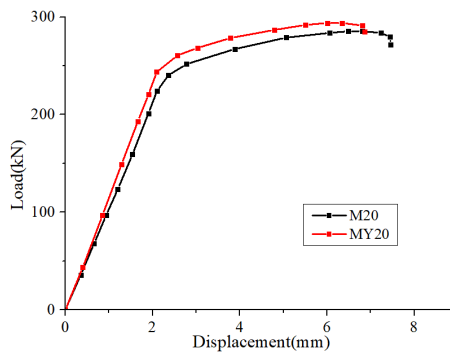
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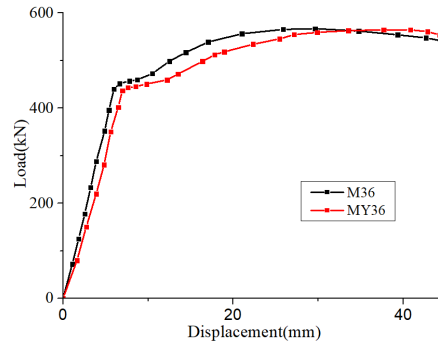
Fig.23. The load-displacement curve of each specimen.

301 Fig.24 shows the failure modes and average load-displacement curve of traditional and new joint specimens  
 302 with the same bolt type and typical bar type. It can be seen from the figure that the load-displacement curves of the  
 303 traditional joint specimens with the same kind of bolt and the new joint specimens are the same, the elastic  
 304 stiffness is similar, and the load to enter the plasticity is identical. But the ultimate tensile strength of the whole  
 305 specimen of the new bolt is slightly higher than that of the entire specimen of the traditional high-strength bolt.

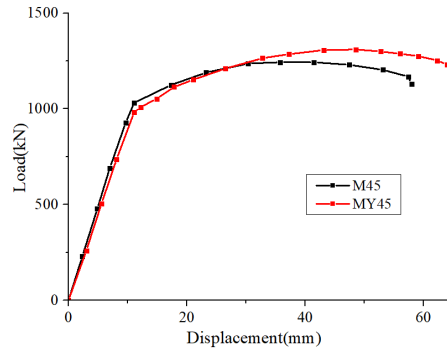


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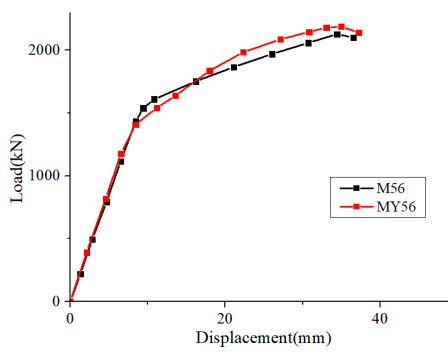
(a)  $\Phi 75.5 \times 3.75 / M20 - MY20$



(b)  $\Phi 114 \times 4 / M36 - MY36$



(c)  $\Phi 159 \times 6 / M45 - MY45$



(d)  $\Phi 180 \times 12 / M56 - MY56$

Fig.24. Failure diagram and load-displacement curve of typical specimens.

## 6. Compressive test of sleeve

The cross-section of the traditional sleeve is circular, and the radial pressure is more uniform. The pressure failure occurs in the center of the pin hole. The inner section of the new sleeve is an octagon, and the pin hole opened by the sleeve is on one face of the octagon. Under pressure, the face with the pin hole is weakened. Therefore, it is necessary to study the compression bearing capacity of the sleeve further.

### 6.1 Test set up

Three sleeves corresponding to MY20 of Q355 material were selected to carry out the radial compressive bearing capacity test of the sleeves. The compressive bearing capacity of the sleeve is the smaller value of the pressure on the end face of the sleeve end and the bolt-ball and the net section pressure at the location of the pin hole of the sleeve. Firstly, the design pressure value of sleeve end face  $N_{ce}$  was calculated according to formula (4). Then the design pressure value of sleeve net section  $N_n$  was calculated according to formula (5).

326 
$$N_{ce} = \left[ \pi \left( \frac{S}{2} + h \right)^2 - 8 \left( \frac{S}{2} \right)^2 \cdot \tan 22.5^\circ \right] \cdot f_{ce}$$
 (4)

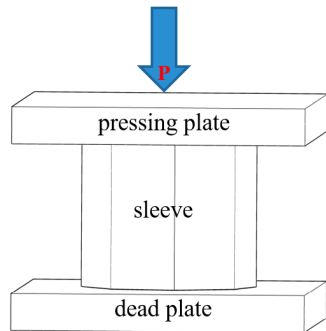
327 
$$N_n = \left[ 8 \left( \frac{S}{2} + h \right)^2 \cdot \tan 22.5^\circ - 8 \left( \frac{S}{2} \right)^2 \cdot \tan 22.5^\circ - h \cdot D_0 \right] \cdot f$$
 (5)

328 Where  $D_0$  is the pin aperture;  $S$  is the distance between the opposite sides of the octagon in the sleeve;  $h$  is  
 329 sleeve thickness;  $f_{ce}$  is the design value of end-face pressure strength;  $f$  is the design value of compressive strength.

330 Through calculation, the design value of net compressive bearing capacity of sleeve corresponding to MY20  
 331 is 214kN, and the design value of end-face bearing capacity is 234kN. Therefore, the control value of compressive  
 332 bearing capacity is 214kN. The loading device was carried out on the microcomputer-controlled electro-hydraulic  
 333 servo universal testing machine, as shown in Fig.25a. Fig.25b is the schematic diagram of the sleeve compressive  
 334 bearing capacity test, and Fig.25c is the diagram of the sleeve compressive test. Above all, load the design value  
 335 of the sleeve compression bearing capacity, observe the deformation of the sleeve. Then load the design value 2  
 336 times, following the deformation of the sleeve. Finally, load the sleeve to failure, test its ultimate compressive  
 337 bearing capacity.



338  
 339 (a) Microcomputer controlled electro-hydraulic servo universal testing machine



340  
 341 (b) Schematic diagram of sleeve compressive bearing capacity test (c) Compression test diagram of the sleeve

342 Fig.25. Compressive bearing capacity test of sleeve.

343 **6.2 Experimental result**

344 When the load is increased to the design value of the bearing capacity of the sleeve, the deformation of the  
 345 sleeve is shown in Fig.26a. The sleeve has no visible deformation, and the overall shape has not changed. When  
 346 the load is loaded to twice the design value of the sleeve compression bearing capacity, the deformation of the  
 347 sleeve is shown in Fig.26b. It can be seen that the sleeve as a whole has no large deformation, only the edge at  
 348 the center position of the pin hole shows outward expansion traces, and it can still be installed and used generally  
 349 after unloading. When the load is loaded until the sleeve has a large deformation, as shown in Figure 26c, the  
 350 load at this time is about 3.14 times the design value of the compression bearing capacity of the sleeve. It can be

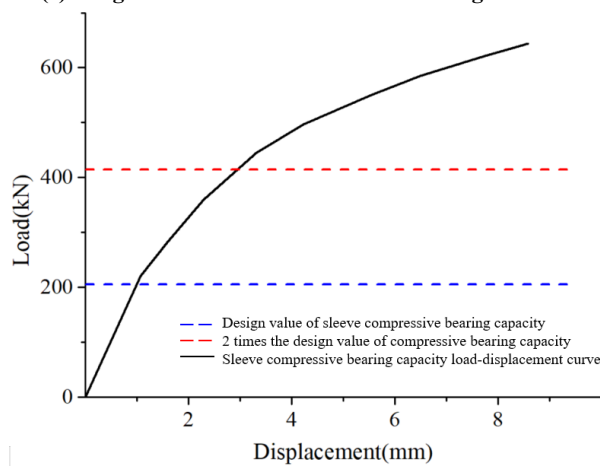
351 seen from the figure that the sleeve bulges outward obviously, and the pin hole is flattened, and the failure was  
 352 overall buckling of the sleeve. The load-displacement curve is shown in Fig.26d. It can be concluded from the  
 353 curve that when the load reaches the design value of the compression bearing capacity of the sleeve, the sleeve  
 354 is in an elastic state and meets the design requirements. When the load comes 2 times the design value of the  
 355 bearing capacity, the slope of the curve changes, and the sleeve yields to some extent, but it still has a high  
 356 compressive bearing capacity. When the load comes 3.14 times the design value of the sleeve compression  
 357 capacity, the sleeve still has a certain compressive bearing capacity. Due to the large deformation of the sleeve,  
 358 it is considered to have reached the ultimate compressive capacity.



359  
 360 (a) Design value of sleeve compression bearing capacity (b) 2 times the design value of the sleeve compression bearing  
 361 capacity



362  
 363 (c) Large deformation occurs when loading to sleeve



364  
 365 (d) Sleeve compressive bearing capacity load-displacement curve

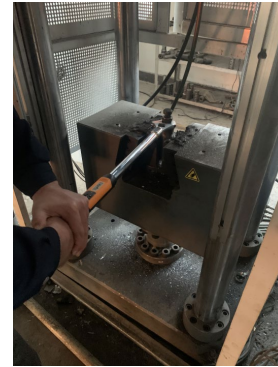
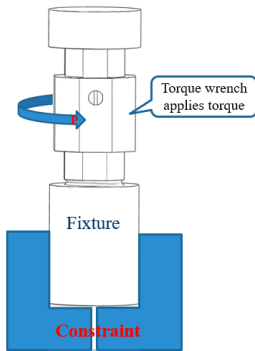
366 Fig.26. The test result of sleeve compressive bearing capacity.

367 **7. Sleeve - bolt and pin torsion bearing capacity test**

368 Torsion bearing capacity tests were carried out on the M20 and MY20 with matching sleeves and pins in order  
369 to compare the torque that the new and traditional joints can undertake during installation. The test set up follows  
370 [19-22]

371 **7.1 Test scheme and device**

372 As shown in Figure 27a, after connecting the sleeve, pin, and the bolt, install the fixture, and turn the sleeve  
373 into the fixture along the bolt thread. When the bolt is screwed into the fixture deep enough, the bolt can no longer  
374 be screwed due to the restriction of the fixture. Use a digital torque wrench (Fig.27b) to rotate the socket until  
375 the pin is cut, and then the torque required to cut the pin can be measured, as shown in Fig.27c. Select two sets  
376 of M20 specimens and measure the torque required to shear the pins. Then 2.5 times of the measured torque and  
377 the maximum torque that can be applied manually by a single person were loaded into two groups of MY20  
378 specimens to observe the torsional performance and its influence on the pin.

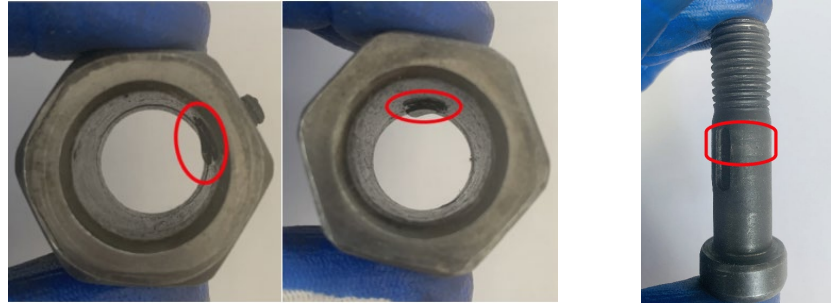


379 (a) Test schematic of torsional bearing capacity (b) Digital torque wrench (c) Test of torsional capacity  
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381

Fig.27. Torsion test.

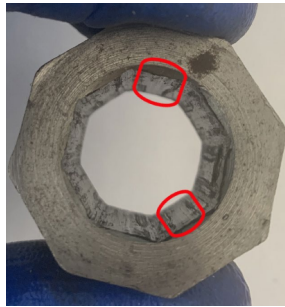
382 **7.2 Experimental result**

383 The maximum torque values of the two sets of M20 bolts corresponding to the pins are  $73.0\text{N}\cdot\text{m}$  and  $72.6\text{N}\cdot\text{m}$ .  
384 The results show that the pin is sheared, and the fracture is a smooth shear surface, as shown in Fig.28a. The pin  
385 in the bolt chute is cut into pieces, and the cut pin is difficult to unscrew from the sleeve. There are apparent shear  
386 marks at the bolt chute, as shown in Fig.28b. The torque value of  $173.4\text{N}\cdot\text{m}$  and the maximum manual torque of  
387  $306.3\text{N}\cdot\text{m}$  was applied to the two groups of MY20 bolts respectively. The results show no change in the pin, and  
388 the accessories can be normally disassembled after unloading the force. In the screw part of the bolt, it can be  
389 seen that the friction marks left by the contact between the octagonal edge and the inner wall of the sleeve, as  
390 shown in Fig.28c and d. The test results show that the new type of joint can bear more than 4 times the torsional  
391 bearing capacity of the traditional joint in the installation process and can bear the maximum torque that can be  
392 applied by manual labor. The pin can still remain in its original state (Fig.27e), and all parts can be disassembled  
393 and used normally after unloading the force.



(a) Pin fracture surface

(b) Cut mark in bolt chute



(c) Friction marks on the inner wall of the sleeve



(d) Friction mark on screw edge



(e) Pin

Fig.28. Results of torque test.

## 8. Numerical simulation

A fine finite element model was established to further study the tensile properties of octagonal high-strength bolts for bolt-ball joints. The accuracy of the finite element model was verified by comparing it with experiments.

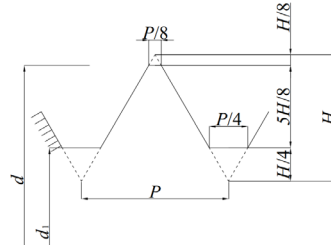
### 8.1 Model set up

The model was established based on ABAQUS. The thread of high-strength bolt has a certain elevation angle along the axial direction of the bolt body. Studies have shown that [23–24] if the thread angle difference is less than  $4^\circ$ , the influence of thread angle on bolt strength can be ignored. The bolt thread angle used in practical engineering is usually less than  $4^\circ$ , so the bolt model does not consider the elevation angle of the thread ring. The refined modeling size was in accordance with the requirements of "General purpose metric screw threads—Basic dimensions" in Chinese (GB/T 196-2003) [25](Fig.29), and the specific size was shown in Table 7. High-strength bolts are made of 40Cr material. The constitutive relation of high-strength bolt and cone head is simplified to a double line model [26], as shown in Fig.30a and b. Stress-strain parameters of steel pipe are obtained from test values, as shown in Fig.30c.

Because the bolted ball joints need to be assembled from different parts, many contacts need to be modeled. In ABAQUS, the possible contact pairs and constraint relationships must be defined. According to "Technical specification for space frame structure" (JGJ7-2010) in Chinese [6], the depth of the bolt into the sphere is greater than 1.1 times the diameter of the bolt. It can be considered that there is no relative sliding between the bolt and the sphere, and binding constraint simulation is selected. The cone head/sealing plate is welded with the member, which is also simulated by binding constraints [27]. Surface to surface contact is selected for the other parts, hard contact is selected for normal contact, penalty contact is selected for tangential connection [28], and the friction coefficient is 0.15[29]. Fig.31 and Table 8 for the contact diagrams between the parts.

One end of the fixture receives constraints in three directions, and the other end exerts a displacement. To ensure the accuracy of the simulation results and the rapid convergence of the calculation, the model is divided

422 by C3D8R three-dimensional solid element [30,31]. Mises stress [32,33] is used as the numerical simulation  
 423 parameter of the model strength. Fig.32 shows each component and the overall model.



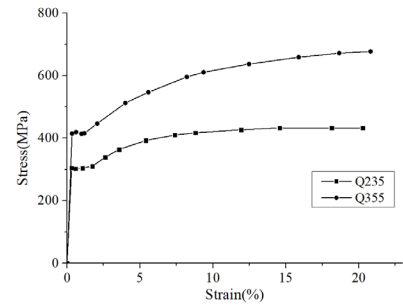
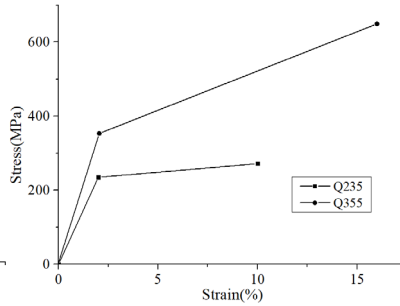
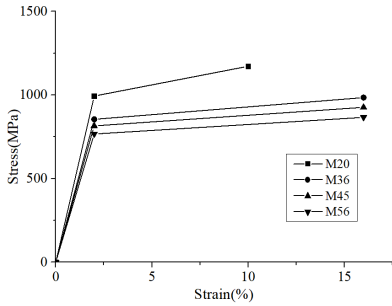
424 **Fig.29.** Thread dimension.

425 **Table 7**

426 Thread dimensions of high-strength bolts.

427

Bolt	$d$ (mm)	$d_1$ (mm)	$H$ (mm)	$P$ (mm)
MY20	20	17.294	2.165	2.5
MY36	36	31.670	3.464	4
MY45	45	40.129	3.897	4.5
MY56	56	51.670	3.464	4

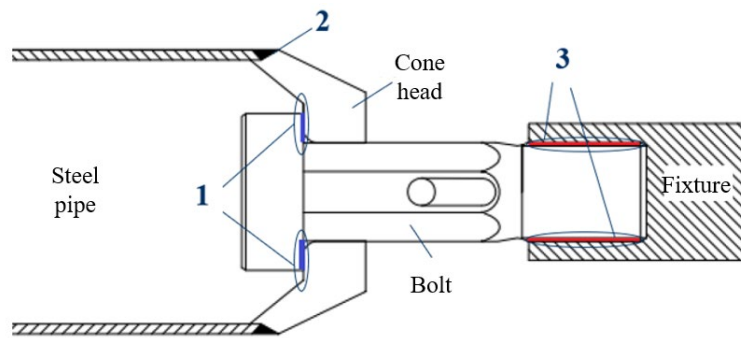


428 (a) Stress-strain curve of high-strength bolt

429 (b) Stress-strain curve of cone head

430 (c) Stress-strain curve of steel pipe

**Fig.30.** Constitutive relation.



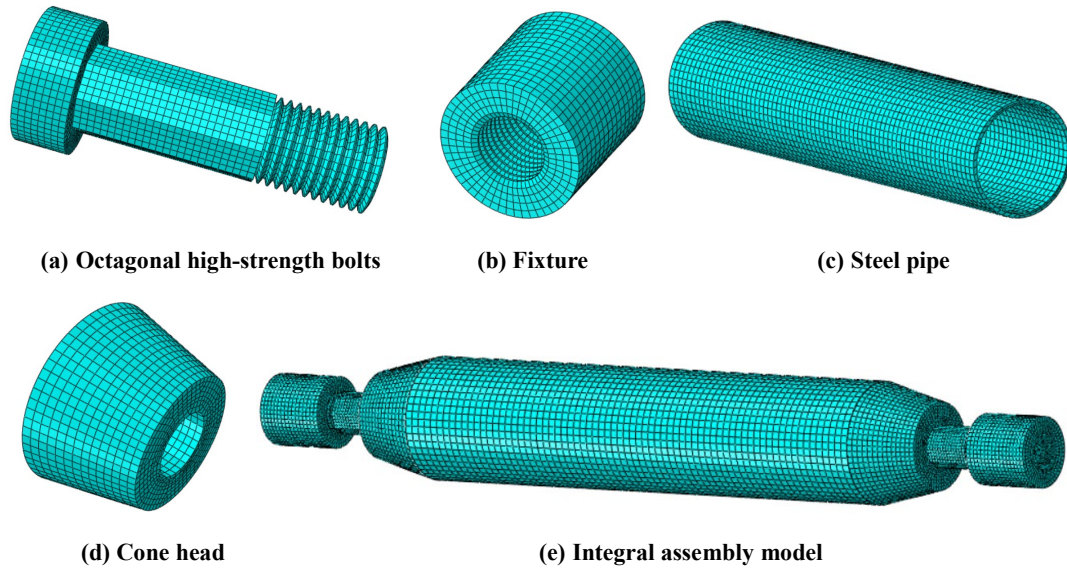
431 **Fig.31.** Contact diagram.

432 **Table 8**

433 Model contact settings.

434

Contact pair number	Description	Contact mode	Interarea faces	Heterotopic faces
1	Nut and cone head	Face to face	Nut	Cone head
2	Member and cone head	Binding	Cone head	Member
3	Thread and fixture	Binding	Fixture	Thread

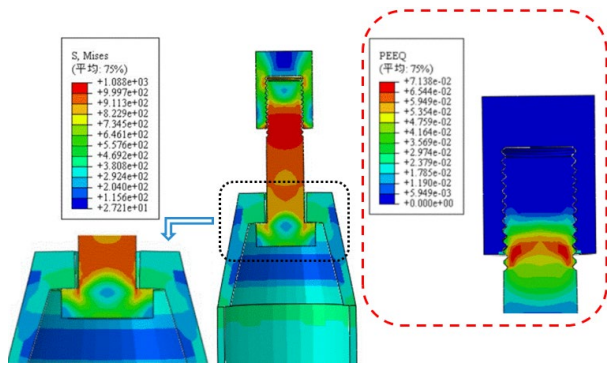


437  
438  
439 **Fig.32.** Finite element model.

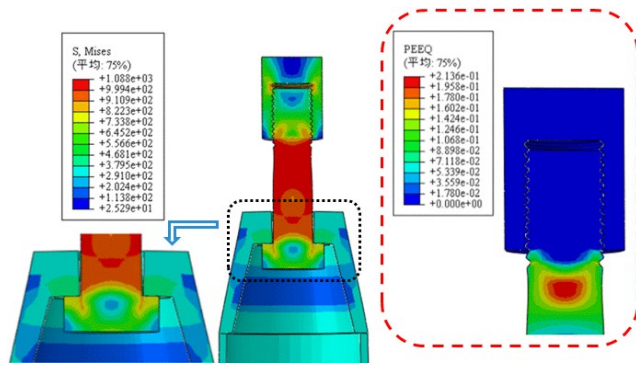
440 **8.2 Tensile simulation result**

441 Fig.33 shows the stress distribution, plastic deformation distribution, and stress distribution at the screw-cone  
 442 head contact point in the finite element analysis (FEA) of the whole specimen. The high-stress state occurs at the  
 443 junction of screw and thread (MY20, MY56) and the middle part of the steel pipe (MY36, MY45). The higher  
 444 plastic deformation in these areas makes the bolt or steel pipe more prone to failure. The plastic deformation of  
 445 MY56 cone head is larger than that of MY20, and the plastic deformation of MY36 and MY45 cone head is  
 446 smaller. These characteristics are consistent with the test results. The stress distribution height of the contact part  
 447 of the nut and the cone head is similar between the traditional bolt type and the new bolt type, indicating that the  
 448 increase of the hole size of the cone head/sealing plate and the diameter of the nut has little effect on the stress  
 449 distribution of the contact part and the bearing capacity of the cone head/sealing plate, which is the same as the  
 450 theoretical analysis results described above.

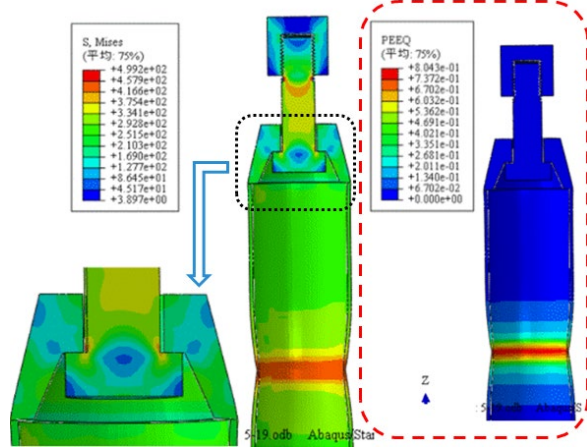
451 Table 9 compares the results of the test and simulation, and Fig.34 compares the load-displacement curves of  
 452 the test and simulation. The following characteristics can be obtained from table 9 and Fig.34: (1) The overall  
 453 shape and peak point of the load-displacement curve simulated by numerical simulation are in good agreement  
 454 with the corresponding test curve, indicating that the numerical simulation can accurately estimate the tensile  
 455 strength of the specimen with an error within  $\pm 10\%$ . (2) Compared with the test, the elastic stiffness of the  
 456 numerical simulation has a slight deviation, and the difference becomes larger with the increase of the bolt type.  
 457 The reason for the stiffness deviation in the elastic stage is mainly due to the partial slippage between the test  
 458 bench and the fixture during the loading process [34-35]. The larger the bolt type, the greater the load applied,  
 459 and the greater the slip between the test bench and the fixture, resulting in a greater difference in elastic stiffness.  
 460 (3) Fig.34a shows the load-displacement curves of specimens M20—MY20, and Fig.34d shows the load-  
 461 displacement curves of specimens M56—MY56. Both of them are bolt fracture failures. Fig.34b shows the load-  
 462 displacement curve of the M36—MY36 specimen, and Fig.34c shows the load-displacement curve of the M45—  
 463 MY45 specimen. Both are steel pipe fracture and failure, and both show the characteristics of steel pipe ductility.



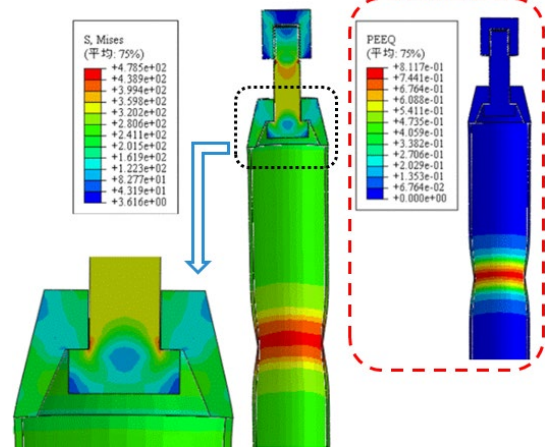
(a)  $\Phi 75.5 \times 3.75$ -MY20



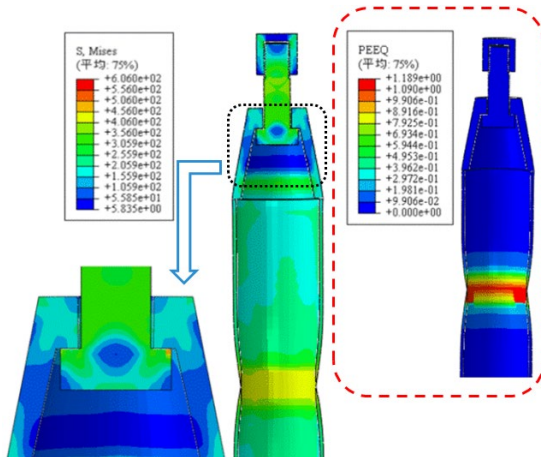
(b)  $\Phi 75.5 \times 3.75$ -M20



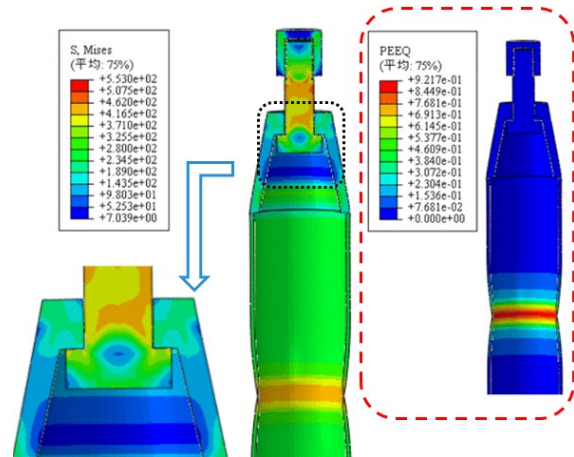
(c)  $\Phi 114 \times 4$ -MY36



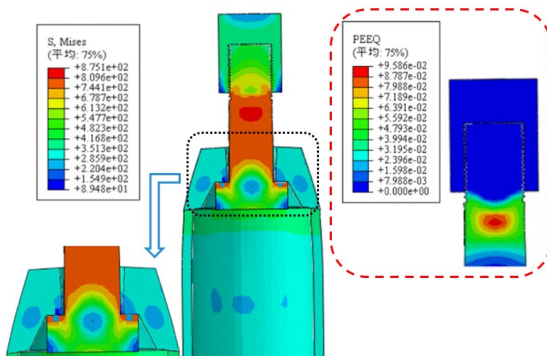
(d)  $\Phi 114 \times 4$ -M36



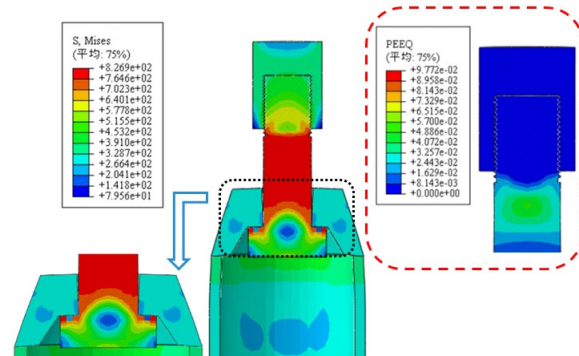
(e)  $\Phi 159 \times 6$ -MY45



(f)  $\Phi 159 \times 6$ -M45



(g)  $\Phi 180 \times 12$ -MY56



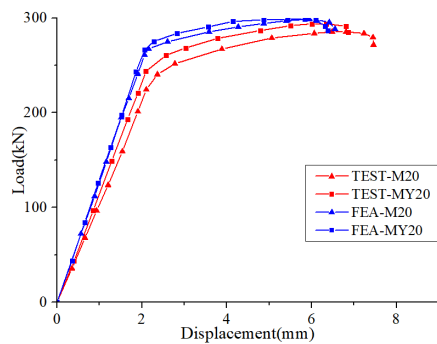
(h)  $\Phi 180 \times 12$ -M56

Fig.33. Finite element analysis results.

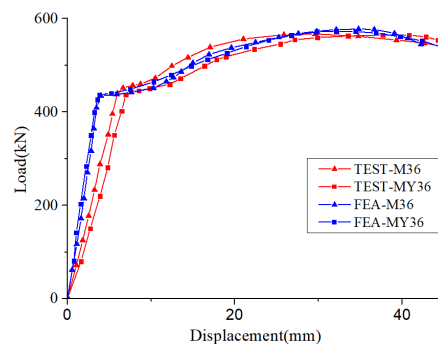
464 Table 9

465 Comparison of test and simulation results.

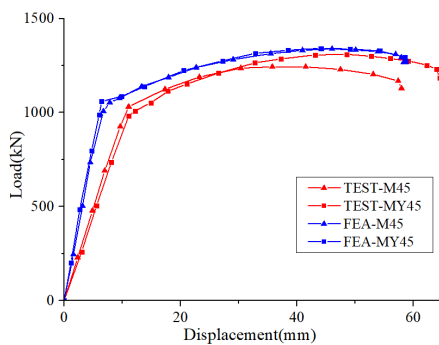
Sample type	Test failure mode	Simulated failure mode	Test tensile capacity (average value) (kN)	Simulate tensile bearing capacity (kN)	Error(%)
M20-Φ75.5	Bolt	Bolt	276	298	7.97
MY20-Φ75.5	Bolt	Bolt	288	299	3.82
M36-Φ114×4	Steel pipe	Steel pipe	578	583	0.34
MY36-Φ114×4	Steel pipe	Steel pipe	581	585	0.68
M45-Φ159×6	Steel pipe	Steel pipe	1227	1331	8.47
MY45-Φ159×6	Steel pipe	Steel pipe	1296	1334	2.93
M56-Φ180×12	Bolt	Bolt	2189	2124	-2.97
MY56-Φ180×12	Bolt	Bolt	2192	2157	-1.59



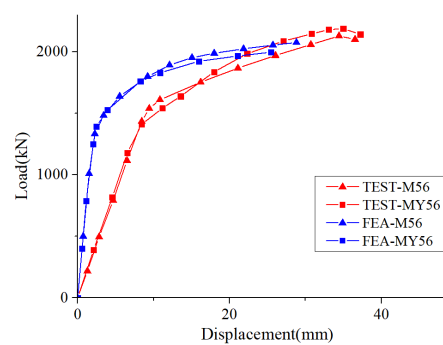
(a) M20—MY20



(b) M36—MY36



(c) M45—MY45



(d) M56—MY56

Fig.34. Load-displacement curves of different types of specimens.

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## 471 9. Conclusion

472 Aiming at the “insufficient tightening” phenomenon of high-strength bolts that is common in bolt-ball joints,  
 473 a new type of bolt-ball joint has been proposed and designed. Explains its anti-false screw mechanism: This node  
 474 relies on the contact transmission force between the octagonal shape in the sleeve and the octagonal section of  
 475 the bolt to screw the bolt into the bolt sphere, and the pin is not affected by the shear force, which avoids the pin  
 476 from shearing. After installation, whether the high-strength bolt is tightened can be directly judged by observing  
 477 the length of the pin tail exposed to the sleeve surface, which overcomes the disadvantage of “insufficient  
 478 tightening” of the high-strength bolt in the construction of the traditional bolt-ball joint. The tensile properties of  
 479 the octagonal high-strength bolts, the tensile properties of the steel pipe-cone head/sealing plate and the whole

480 specimen of the bolt, the bearing properties of the sleeve, and the torsional capacity of the joint installation were  
481 studied. The conclusions are as follows:

482 (1) Four common bolt types, MY20, MY36, MY45, and MY56, were selected to carry out the unidirectional  
483 tensile test with 12 octagonal high-strength bolts with 3 samples of each type. The tensile load of one specimen  
484 MY45 exceeded the maximum tensile load specified by the standard by 2.36%. The failure load, failure position,  
485 failure mode, and elongation of the other octagonal high-strength bolts all meet the requirements of the current  
486 standard "High-strength bolts for joints of space grid structures" in Chinese (GB/T 16949-2016).

487 (2) The tensile test of the whole specimen containing steel pipe—cone head/sealing plate and bolt shows three  
488 failure modes, including steel pipe failure, bolt failure, and weld failure. The uniaxial tensile load-displacement  
489 curve of the integral test piece containing the steel pipe, cone head/sealing plate, and the traditional high-strength  
490 bolt and the integral test piece of the octagonal high-strength bolt is the same, the elastic stiffness is similar, and  
491 the plastic load force and ductility are similar. However, the ultimate tensile strength of the octagonal high-  
492 strength bolt integral test piece is slightly higher than that of the traditional high-strength bolt integral test piece.

493 (3) A detailed finite element (FEA) model was established for the whole test piece containing the steel pipe—  
494 cone head/sealing plate and bolts for simulation analysis. The analysis results show good consistency with the  
495 failure mode and failure load shown in the test, and can clearly show the stress distribution. However, due to the  
496 slippage between the test equipment and the fixture, the stiffness of the bolted ball joint cannot be predicted  
497 accurately.

498 (4) The opening size of octagonal high-strength bolts corresponding to the cone head/sealing plate is about 8%  
499 more than that of the traditional cone head/sealing plate. Tests and finite element analysis show that the diameter  
500 of the octagonal high-strength bolts is designed to be 1mm or 2mm larger than the diameter of the traditional  
501 high-strength bolts, which can make the bearing capacity of the new cone head/sealing plate equal to the  
502 traditional cone head/sealing plate.

503 (5) The compression test of the new sleeve shows that its ultimate compressive bearing capacity exceeds its  
504 compressive design bearing capacity by more than 3 times.

505 (6) The torque bearing performance of the new type of joint and the traditional joint during installation is  
506 compared through tests. The results show that because the bolt is screwed into the bolt sphere by the contact force  
507 of the sleeve and the bolt instead of shear force from the pin, the torque that the new joint can withstand during  
508 the installation process is much greater than that of the traditional joint.

509

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