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STUDY ON PREFABRICATED CONNECTOR OF DOUBLE-LAYER RECIPROCAL FRAME

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ABSTRACT

A kind of lattice-type steel member is presented and a kind of prefabricated connector suitable for the connection between lattice-type steel members are proposed. The mechanical properties of the connectors are analyzed by using the finite element numerical simulation software ABAQUS. The connectors meet the design goals of the stiffness of connection stronger than members. Parameterized analysis is carried out on the prefabricated connector, and the flexural stiffness expression of the connector is obtained. The suggested values of each component of the prefabricated connectors are given based on the size of connected lattice-type steel members.

KEYWORDS

Double-layer reciprocal frame; Prefabricated structure; Prefabricated connector; Steel structure

INTRODUCTION

The number and variety of members and joints in the traditional large span spatial structure are numerous. The complexity of the structure leads to special shape of the member and the complexity of joints. It is often the case that lots of members are converged at one joint, which causes the consequence that difficulty and the cost of construction both are increased largely [1-3]. Figure 1 shows the roof structure of Beijing Daxing Airport Terminal in China.

The hex-tri reciprocal frame is a special structure of rotational symmetry. The members support each other, each member not only supports the adjacent members but also is supported by another adjacent members, so all members are subjected to the similar mechanical characteristics [4-6]. Members of reciprocal frame are interconnected, which makes the forms of members and joints simple and unified [7-8]. The large span spatial structure can be realized by assembling small-size members of the reciprocal frame, which has a promising future in prefabricated building [9-10].

Fig. 1 - The Roof Structure of Beijing Daxing Airport Terminal

Reciprocal frame is of a long history. The unique structure makes its connections play a crucial part to ensure the reliability of reciprocal frame [4-5]. The joints of reciprocal frame are various. A model of arch bridge connected by inter-locked is shown in Figure 2 [3]. This type of connection depends on frictional force to guarantee the reliability of the structure. This kind of friction-driven connections is very simple. However, the strength and rigidity of the structure is weak which results in the short span of reciprocal frame [11-12]. With the development of reciprocal frame, lashed connection and notched connection appeared [5]. Because the low strength and small rigidity of the connection, reciprocal frame cannot reach larger span [14-15].

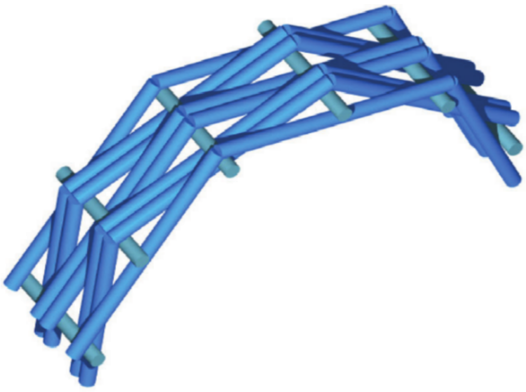


Fig. 2 - Model of Chinese laminated beam bridge

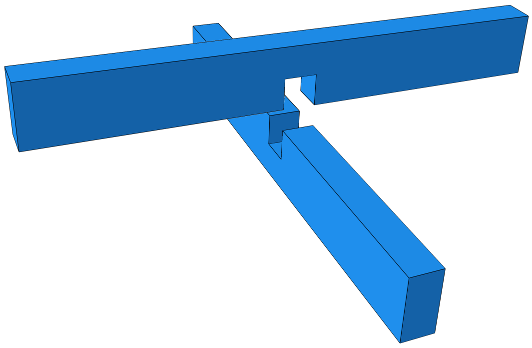


Fig. 3 - Notched connection

In 1976, the first patent of connector in reciprocal frame, bolted connectors, was proposed by Bijnen. He suggested to loop the circular hollow sections via threaded pins to form reciprocal frame [14-15]. The connector is very simple, and is of high strength and great rigidity. However, this connector requires high precision of reserved holes and threaded pins which results in great difficulties for construction and even reducing the efficiency of construction. In addition, two adjacent members connected by this connector rotate result in small rigidity and low strength of the whole structure [15]. The adjustable connector is a kind of prefabricated connection. The strength and rigidity of this kind of connector is much higher, and the unique structure compensates for installation error of the members [15]. However, the adjustable connector is only suitable for single-layer reciprocal frame, which cannot reach large span.

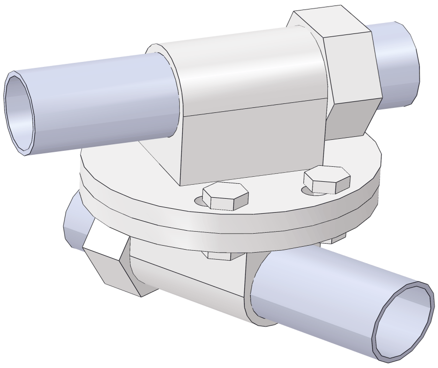


Fig. 4 - Adjustable connector

Fig. 5 - Single-layer reciprocal frame

The extant buildings of reciprocal frame, whether roof structures or landscape structures, are single-layer reciprocal frames. Due to low strength and low stiffness of members, the span of the structure is small. The members of single-layer reciprocal frame are mainly subjected to bending moment, but the bending stiffness of the member is low, which is the main reason for low stiffness of the single-layer reciprocal frame [16-18]. As shown in Figure 6, by transforming the members to lattice-type members, the transformation of the single-layer reciprocal frame to the double-layer reciprocal frame is realized, and the stiffness and strength of the structure have been improved. The double-layer reciprocal frame retains the features and advantages of the reciprocal frame and the strength and stiffness have been improved [17-19].

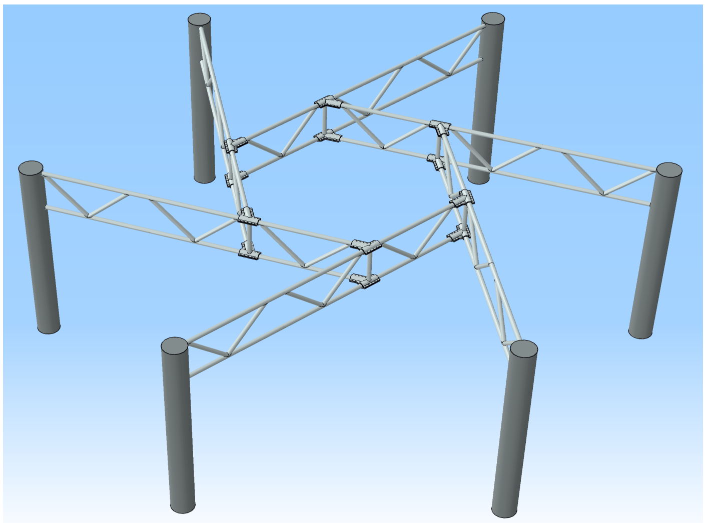


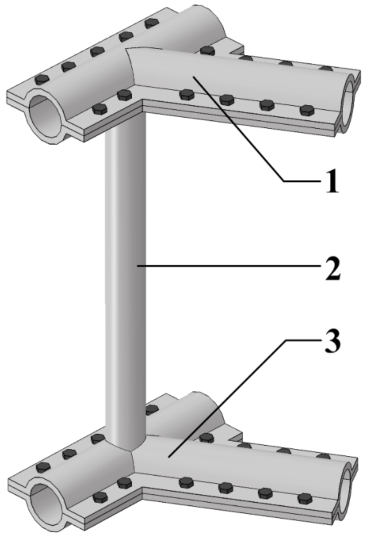
Fig. 6. - A fan of double-layer of reciprocal frame

PREFABRICATED CONNECTOR

Prefabricated Connector

The reliability of the structure connection is crucial. In order to get over the shortcomings of existing joints of reciprocal frame, a kind of prefabricated connector is invented, which is rigid and suitable for alignment between lattice-type members, as shown in Figure 7. The prefabricated connector consists of upper structure, middle structure and lower structure: upper clamping structure 1, middle supporting structure 2 and lower clamping structure 3. The upper clamping structure and lower clamping structure have the same structural form. The upper clamping structure and the lower clamping structure are parallel intervals set. The middle supporting structure is set vertically with the clamping structures.

As shown in Figure 7 and Figure 8, the two holes with circular sections in each clamping structure are formed by tightening high-strength fastening bolts. The external force works on the upper clamping structure. By setting middle supporting structure, the force can be bear by top and bottom chord. Because the middle supporting structure transmits part of the external force to the bottom chord, the concentration phenomenon of stress at the joints of the lattice type members has been reduced, the material utilization rate has been improved.



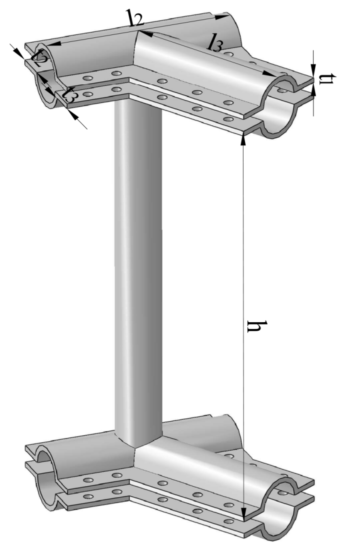


Fig. 7 - Prefabricated connector *Fig. 8 - Parameters of prefabricated connector*

Lattice type member

The bending moment is mainly beared by the members of reciprocal frame. In order to solve the problems that low stiffness of the single-layer reciprocal frame. A lattice type steel member suitable for double-layer reciprocal frame is designed, as shown in Figure 9. The position of prefabricated connectors is reserved in the chord member to facilitate the connection between the lattice type steel member and the prefabricated connectors. And some of the bending moment in the member is converted into axial force. The utilization rate of material has been improved and the stiffness and strength of the structure has been enhanced.

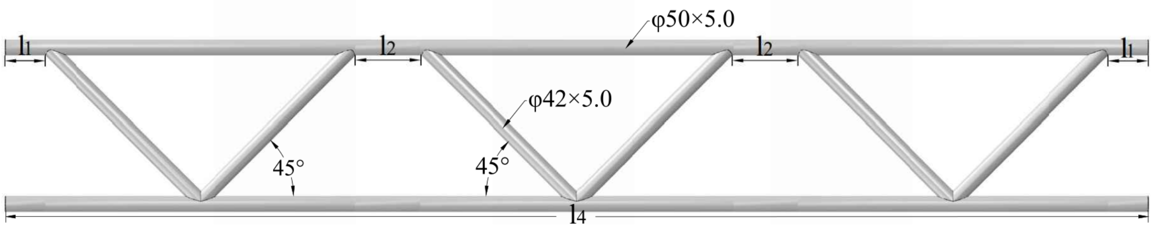


Fig. 9 - Lattice type member

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NUMERICAL ANALYSIS OF PREFABRICATED CONNECTOR

As is shown in Figure 10, a three dimensional entity model of a reciprocal frame fan including the prefabricated connectors and the lattice type steel members made of Q235 steel has been created, using the finite element model software Abaqus CAE, to study the mechanical properties of the prefabricated connector. The parameters of each part of the prefabricated connector and the lattice type steel member are shown in table1. The vertical loads are mainly borne by double-layer reciprocal frame which are transmitted to the whole structure by the connectors. Fixed constraints are applied to the ends of the lattice type members, and the vertical downward pressure is applied to the upper surface of the connectors and the gravity of the connectors and members is applied to the numerical model to study the mechanical characteristics of the connectors. In Figure 11, the ratio of the vertical direction displacement of section A to l_1 is the connector's rotation angle around the x-axis.

Tab. 1: The parameters of each part of the connector and the lattice type steel

Geometric Parameters	t_1	t_2	t_3	t_4	l_1	l_2	l_3	l_4	h
Value	8	34	26	6	158	230	230	4420	500

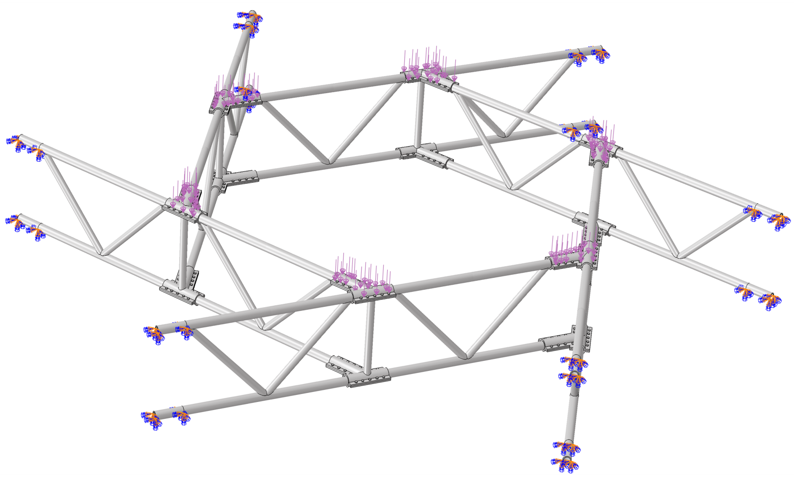


Fig. 10 - The numerical model of reciprocal frame

Fig. 11 - Section A of the connector

In order to study the characteristics of the prefabricated connectors and the failure mechanism of the double-layer reciprocal, the pressure has been constantly increased. When the plastic hinge was formed, the pressure was increased to 2.46 MPa. In the fan of reciprocal frame, every member and connector are in the same condition of stress, so a lattice type steel member and an prefabricated connector are taken to analyse the stress condition.

As can be seen from Figure 12, the connecting part of the web member and upper chord of the lattice-type steel member has shown that the stress of the full section has been reached to 235 MPa and the plastic hinge has been formed, so that the lattice-type steel member has been damaged.

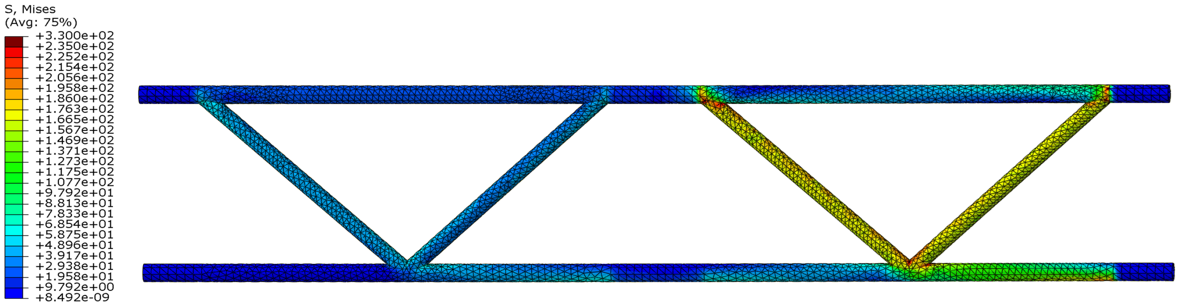


Fig. 12 - Stress nephogram of the lattice type member under pressure/Pa

It can be seen from Figure 13 that most stress elements of the prefabricated connectors are still in the elastic stage, and few of the stress elements of the edge part exceeds 235 MPa. In conclusion, the strength of the connection is higher than the strength of the members. The rotation angle of the connector is only 1.01×10^{-3}rad while the plastic hinge of the member was formed. Hence the rigidity of the prefabricated connector of the X-axis is very large.

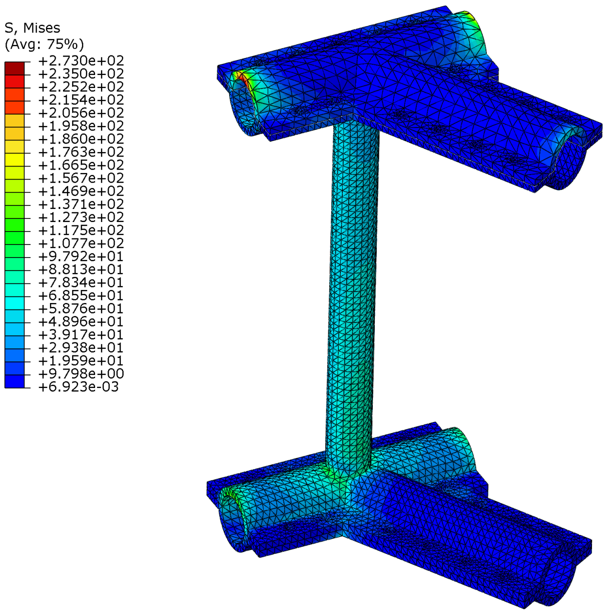


Fig. 13 - Stress nephogram of the prefabricated connector/Pa

CALCULATION MODEL OF THE CONNECTOR

As can be seen from the analysis in the previous section, when plastic hinge is generated at the connecting part of the web member and the upper chord of the lattice steel member, almost all stress elements in the prefabricated connectors are still in the elastic stage.

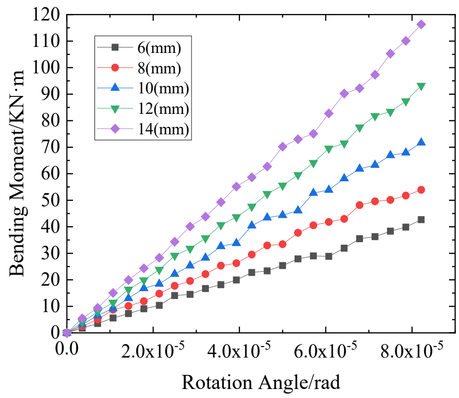
After finite element analysis, parameters l_3, l_2, l_4, and h have little effect on the finite element analysis of the prefabricated connector. Therefore l_3=l_2= 230 mm, l_4= 4420 mm, h= 500 mm are fixed values. And using this type lattice-steel member of these parameters, when the lattice-steel member is damaged, the stress element of the connector is about to reach the yield stress of 235 Mpa. The problem that the lattice-steel member is too strong and the failure of the prefabricated connector occurs before the lattice-steel member enters the yield stage is avoided, and the problem that the stress of the prefabricated connector is too small when the lattice-steel member is damaged is avoided.

In order to analyze the complete mechanical characteristics of the prefabricated connectors, the size of each part of the connectors were changed respectively, and the mechanical properties of the prefabricated connectors were analyzed according to the arc length method. The other values of each part in numerical model of parametric analysis are shown in Table 2.

Tab. 2 - Values of connectors in numerical model of parametric analysis

No.	1	2	3	4	5	6	7	8	9	10
t_1/mm	6	8	10	12	14	8	8	8	8	8
t_2/mm	34	34	34	34	34	30	32	34	36	38
t_4/mm	6	6	6	6	6	6	6	6	6	6
l_1/mm	168	168	168	168	168	168	168	168	168	168
l_2/mm	250	250	250	250	250	250	250	250	250	250
f/MPa	235	235	235	235	235	235	235	235	235	235
No.	11	12	13	14	15	16	17	18	19	20
t_1/mm	8	8	8	8	8	8	8	8	8	8
t_2/mm	34	34	34	34	34	34	34	34	34	34
t_4/mm	4	6	8	10	12	6	6	6	6	6
l_1/mm	168	168	168	168	168	158	163	168	173	178
l_2/mm	250	250	250	250	250	250	250	250	250	250
f/MPa	235	235	235	235	235	235	235	235	235	235

No.1-5 in Table 2 are used to establish three-dimensional solid numerical models of ABAQUS. Grave force has been applied and pressure has applied to the connectors. In Model 1-5, only the parameter t_1 has been changed and other parameters remain unchanged. Thus only t_1 is the factor affecting the flexural rigidity of prefabricated connectors. It can be seen from Figure 14 that the rotation angles of the prefabricated connectors around x-axis are approximately directly proportional to the bending moments on section A, and the flexural rigidity of the connector has been increased obviously with the increase of t_1. After analysis and calculation, the flexural rigidity curve of prefabricated connectors with different sizes of t_1 is shown in Figure 15.



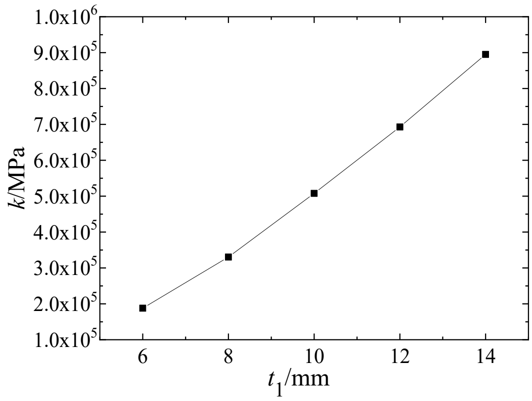


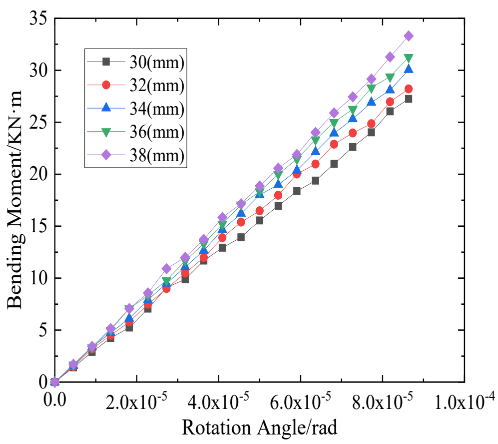
Fig.14 - No.1-5 Numerical model of rotation angle *Fig.15 - No.1-5 Relation curve*

As shown in the Figure 15, the flexural rigidity *k* of the prefabricated connector of the x-axis is of an approximate linear relationship with t_1, and the formula is shown below:

$$k=90626t_1+44781 \quad (3.1)$$

Related coefficient: R^2=0.98

The relationship between t_2 and *k* is analyzed in the same way. The bending moment on section A and the Angle curve of prefabricated connectors are shown in Figure 16. It can be seen from Figure 16 that the rotation angle of the prefabricated connectors around the x-axis is directly proportional to the bending moment, and the rigidity of the prefabricated connector is weakly increased with the increase of t_2. After analysis and calculation, the flexural rigidity curve of prefabricated connectors with different sizes of t_2 is shown in Figure 17.



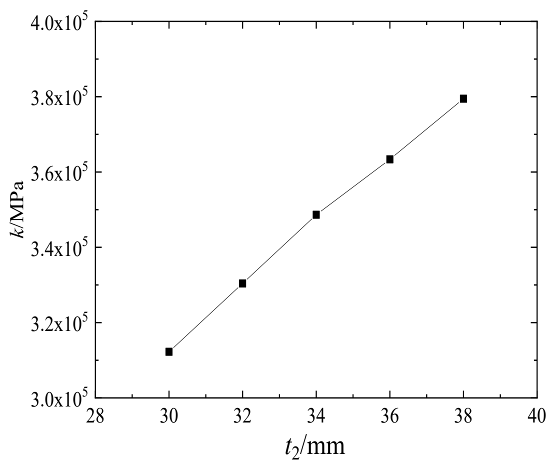


Fig. 16 - No.6-10 Numerical model of rotation angle *Fig. 17. No.6-10 Relation curve*

As is shown in Figure 17, the flexural rigidity *k* of the prefabricated connector of the x-axis is of an approximate linear relationship with t_2, and the formula is shown below:

k=1640t_2+277890 (3.2)

Related coefficient: R^2=0.97

The relationship between t_3 and k is analyzed in the same way. The bending moment on section A and the Angle curve of connectors are shown in Figure 18. It can be seen from Figure18 that the rotation angle of the connectors around the x-axis is directly proportional to the bending moment, and the flexural rigidity of the prefabricated connector is weakly increased with the increase of t_4. After analysis and calculation, the flexural rigidity curve of prefabricated connectors with different sizes of t_4 is shown in Figure19.

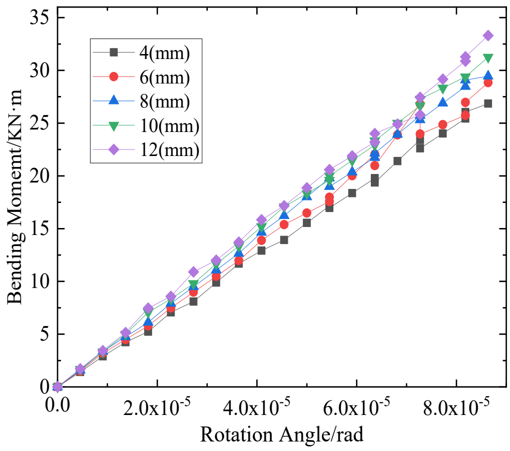


Fig. 18 - No.11-15 Numerical model and rotation angle

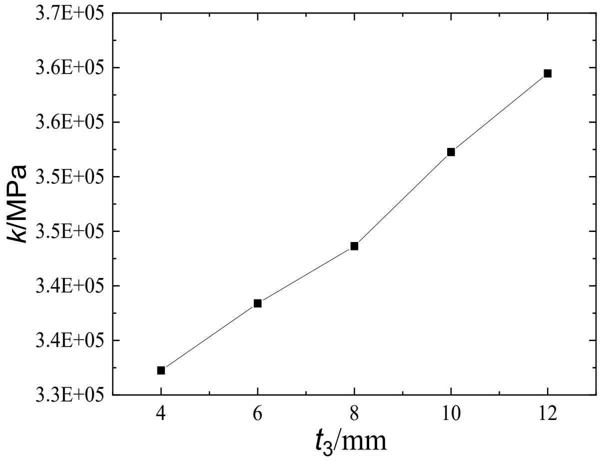


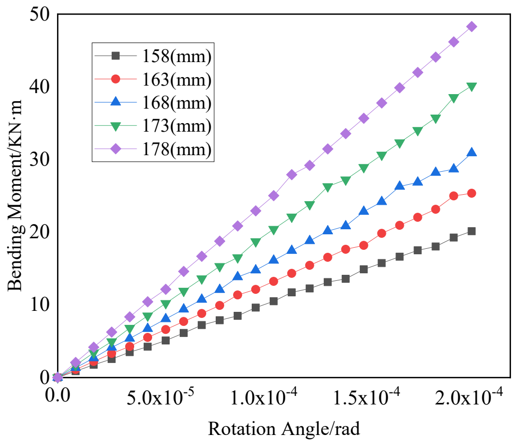
Fig. 19 - No.11-15 Relation curve

As is shown in Figure 19, the flexural rigidity k of the prefabricated connector of the x-axis is of an approximate linear relationship with t_3, and the formula is shown below:

k=2623t_3+322655 (3.3)

Related coefficient: R^2=0.95

The relationship between l_1 and k is analyzed in the same way. The bending moment on section A and the Angle curve of prefabricated connectors are shown in Figure 20. It can be seen from Figure 20 that the rotation angle of the prefabricated connectors around the x-axis is directly proportional to the bending moment, and the flexural rigidity of the prefabricated connector is significantly increased with the increase of l_1. After analysis and calculation, the flexural rigidity curve of prefabricated connectors with different sizes of l_1 is shown in Figure 21.



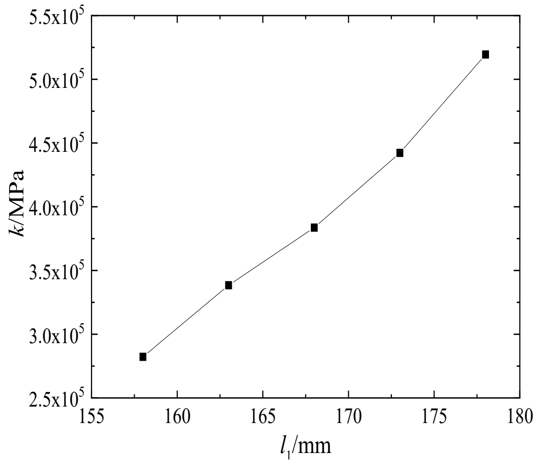


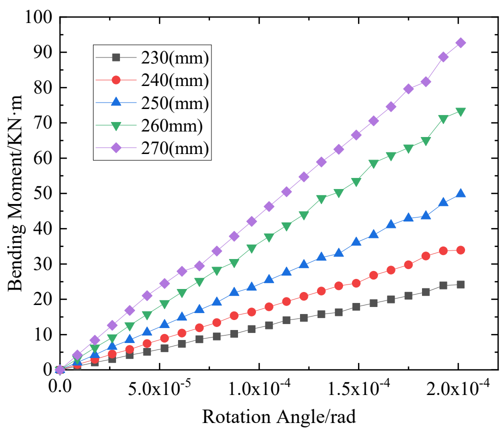
Fig.20. No.16-20 Numerical model of rotation angle Fig.21. No.16-20 Relation curve

As is shown in Figure 21, the flexural rigidity k of the prefabricated connector of the x-axis is of an approximate linear relationship with l_1, and the formula is shown below:

$$k=29652l_1+163655 \tag{3.4}$$

Related coefficient: R^2=0.96

The relationship between l_2 and k is analyzed in the same way. The bending moment on section A and the Angle curve of prefabricated connectors are shown in Figure 22. It can be seen from Figure 22 that the rotation angle of the prefabricated connectors around the x-axis is directly proportional to the bending moment, and the flexural rigidity of the prefabricated connector is significantly increased with the increase of l_2. After analysis and calculation, the flexural rigidity curve of prefabricated connectors with different sizes of l_2 is shown in Figure 23.



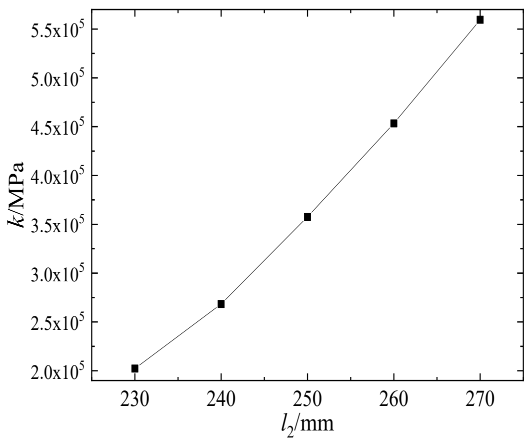


Fig. 22 - No.21-25 Numerical model of rotation angle Fig. 23 - No.21-25 Relation curve

As is shown in Figure 23, the flexural rigidity k of the prefabricated connector of the x-axis is of an approximate linear relationship with l_2, and the formula is shown below:

$$k=7251l_2+74353 \tag{3.5}$$

Related coefficient: R^2=0.97

The relationship between *f* and *k* is analyzed in the same way. The bending moment on section A and the Angle curve of connectors are shown in Figure 24. It can be seen from Figure 24 that the rotation angle of the connectors around the x-axis is directly proportional to the bending moment, and the flexural rigidity of the connector is significantly increased with the increase of *f*. After analysis and calculation, the flexural rigidity curve of prefabricated connectors with different sizes of l_2 is shown in Figure 25.

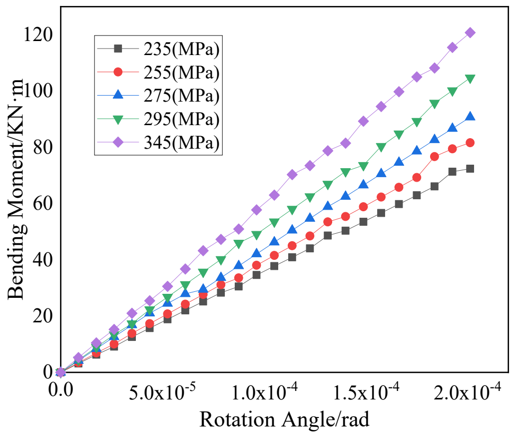


Fig.24 - No.26-30 Bending moment and rotation angle

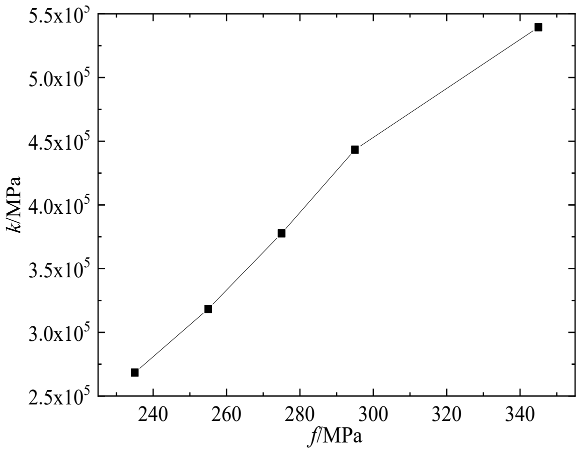


Fig.25 - No.26-30 Relation curve

As is shown in Figure 25, the flexural rigidity *k* of the prefabricated connector of the x-axis is of an approximate linear relationship with *f*, and the formula is shown below:

$$k=6843f+86219 \tag{3.6}$$

Related coefficient: R^2=0.94

As can be seen from the above expressions, the coefficient of k with t1 is 90626, much higher than the coefficient of *k* with t_2, t_4, l_1, l_2 and *f*. Therefore the value of flexural stiffness k is taken to be most influenced by the change in parameter t_1.

As can be seen from the above analysis, it can be concluded the rigidity *k* of the prefabricated connector is of a linear relationship with the parameters t_1、t_2、t_3、l_1、l_2 and *f*. However, according to the formulas, the degree of influence of each parameter on the flexural rigidity *k* is different, the coefficient of *k* with t_1 is 90626, much higher than the coefficient of *k* with t_2, t_3, l_1, l_2 and *f*. Therefore, the value of the flexural rigidity *k* is most affected by the change of the parameter t_1. The formula of $\frac{k}{t_2 t_3 l_1 l_2 f}$ and t_1 are as follows:

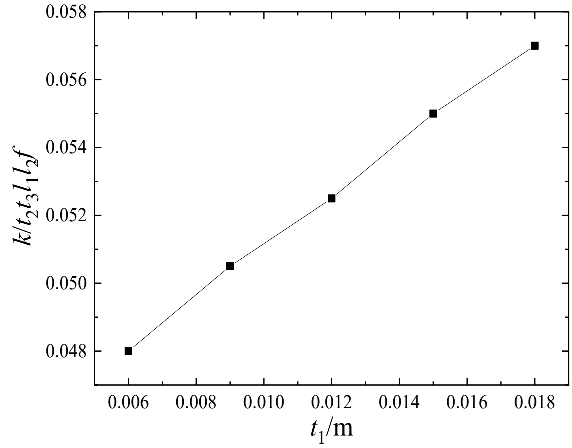


Fig. 26 - Curve of $\frac{k}{t_2 t_3 l_1 l_2 f}$ and t_1

The formula is shown below:

$$\frac{k}{t_2 t_3 l_1 l_2 f} = 0.81 t_1 + 0.02 \tag{3.7}$$

Related coefficient: R^2=0.9985.

In conclude, the formula of flexural rigidity k of the prefabricated connector is as follows:

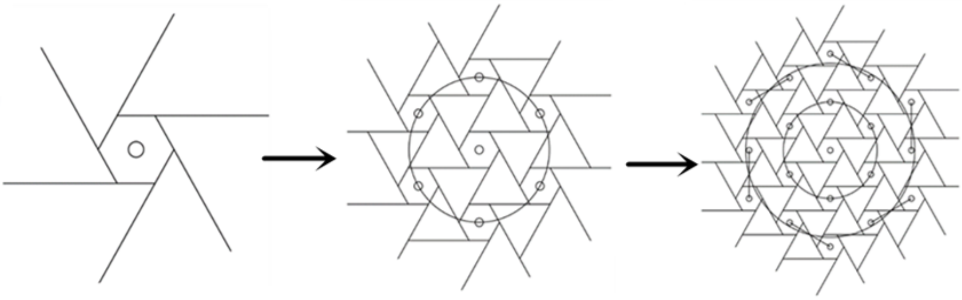
$$k = t_2 t_3 l_1 l_2 f \left(0.81 t_1 + 0.02\right) \tag{3.8}$$

For the selection of the size of the prefabricated connector, the design goal is to ensure that the prefabricated connector is still in elastic state when the lattice type steel member is damaged, and at the same time, to reduce the size of each part and reduce the use of materials. The chord and web member of the lattice type steel member are circular hollow sections. The outer diameter of the steel pipe is d_s, and the wall thickness is t_s. The diameter of the web member is 0.8d_s, and the wall thickness is t_s. After calculation and analysis, the suggested sizes of each part of the prefabricated connector are t_1=1.4t_s, t_2=8t_s, t_3=1.2t_s, t_4=1.2t_s, l_1=5d_s+5t_s, l_2=3d_s+5t_s. The diameter of the fastening bolt is 4t_s, and the thickness of bolt protection layer is 4t_s. Specification of fastening bolt should not be smaller than M16 type high strength bolt.

DOUBLE-LAYER HEX-TRI PREFABRICATED RECIPROCAL FRAME

The grid of hex-tri reciprocal frame

As is shown in Figure 27, the grid of hex-tri reciprocal frame is regular and can be extended infinitely to all sides through the annular array. Under the requirements of rigidity, strength and stability, the double-layer hex-tri reciprocal frame can be extended to the outer ring and reach a larger span according to the expansion law of the hex-tri grid of reciprocal frame.[21]



(a) The basic configuration (b)Once extension (c)Twice extension

Fig. 27 - The law of extension of hex-tri grid of reciprocal frame

Double-layer hex-tri prefabricated reciprocal frame

The existing reciprocal frame examples are mainly single-layer reciprocal frame. Due to low strength and low stiffness of members, the span of single-layer reciprocal frame is small. The members of single-layer reciprocal frame are mainly subjected to bending moment, but the bending stiffness of the member is low, which is the main reason for low stiffness of the single-layer reciprocal frame. By transforming the members to lattice-type members, the transformation of the single-layer reciprocal frame to the double-layer reciprocal frame is realized, and the stiffness and strength of the structure have been improved. The double-layer reciprocal frame retains the features and advantages of the reciprocal frame and the strength and stiffness have been improved.

As is shown in Figure 28, according to the geometric extension law of the grid of hex-tri reciprocal frame, the double-layer hex-tri prefabricated steel reciprocal frame can be built, using the prefabricated connectors and lattice type steel members designed in this paper. The joints of the structure are crucial, and the reliability of the prefabricated connector can be guaranteed, and the formula of flexural rigidity of the prefabricated connector has been calculated.

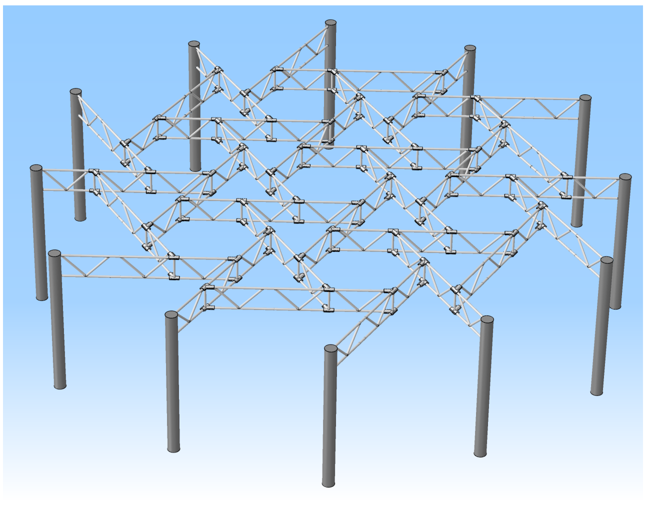


Fig. 28 - Double-layer reciprocal frame

Double-layer hex-tri prefabricated steel reciprocal frame stress cloud

The calculated bending stiffness equation of prefabricated connector (3.8) was input into the ABAQUS finite element connector. Based on the once extension of the hex-tri grid, the finite element numerical model of ABAQUS of double-layer hex-tri steel reciprocal frame was established based on beam elements and hinged connectors. The element type of the finite element numerical model is B31, and the material is Q235 steel. The total length of the members in the numerical model is 4140 mm, the diameter of the circular hollow section is 50mm, and the wall thickness is 5 mm, and the diameter of the circular hollow section web member is 42 mm and a wall thickness of 5mm. Fixed constraints were applied external endpoints of the numerical model, and the roof load of 0.9 kN/m^2 was evenly applied at the joints.

The stress of the double-layer hex-tri steel reciprocal frame formed by the once extension is shown as Figure 29. The stress of the lower chord at the support is the largest, which is 100.4 MPa, less than the yield strength of Q235 steel.

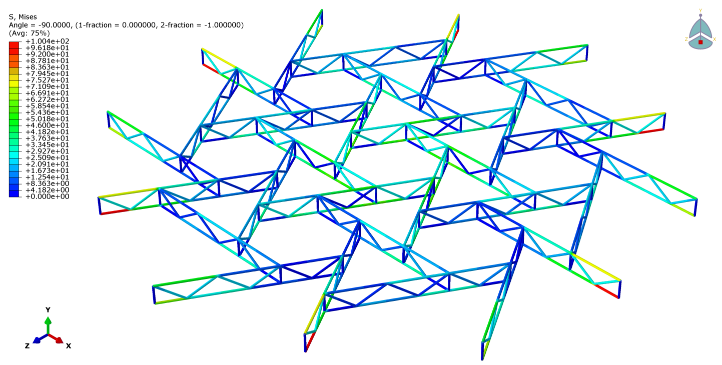


Fig. 29 - Double-layer hex-tri prefabricated steel reciprocal frame stress cloud

CONCLUSION

(1) A lattice-type steel member is presented and a kind of prefabricated connector suitable for the connection between lattice-type steel members are proposed. The mechanical properties of the connectors are analyzed by using the finite element numerical simulation software ABAQUS. The connectors meet the design goal of the strength and rigidity of joints stronger than members.

(2) Parameterized analysis is carried out on the prefabricated connector, and the formula of flexural rigidity of the prefabricated connector has been calculated. The suggested values of each part of the prefabricated connectors are given based on the size of connected lattice type steel members

(3) According to the geometric extension law of the grid of hex-tri reciprocal frame, the double-layer hex-tri prefabricated steel reciprocal frame can be built, using the prefabricated connectors and lattice type steel members designed in this paper.

DECLARATION OF COMPETING INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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