Numerical Simulation Study on Bolted Joints of Steel-wood Structures

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Abstract. As one of the most widely used rigid connections, bolted joints have the advantages of convenient loading and unloading, increased prestressing to prevent loosening, and no change in material composition at the joints. In this paper, six sets of test pieces are designed, and the monotonic loading is performed. The bearing capacity of the joints under the two parameters of bolt margin and wood characteristics is analyzed, and compared with the theoretical value, the reliability of the finite element simulation results is increased.

1. Introduction
The steel-wood structure is a new type of structure that effectively combines the steel structure and the wood structure. It has the durability of the traditional steel structure and the good compressive and compressive performance of the wooden structure. It is easy to be applied to the support rod of the large-span structure with Pieces, light weight, environmental protection, low energy consumption, insulation and corrosion resistance [1].

At present, many researchers have conducted in-depth research on the joint test of steel-wood structural bolting: Li Feng [2] found that the screw force in the screw group is uneven, and the screw near the centroid of the screw group can resist seismic energy consumption; Enzhen Zhu [3] proposed a calculation formula for the bearing capacity of bolted joints by carrying out the bearing pressure test and bolting performance test of the larch and Pinus sylvestris var. mongolica; Kezhen Liu et al [4] proposed the force failure mode includes the tensile failure of the steel plate and the compression of the wall of the hole.

In this paper, six sets of test pieces are designed, and the monotonic loading is carried out. The bearing capacity of the joints under the two parameters of the bolt margin (45mm, 52.5mm, 60mm) and the wood characteristics (red pine, glulam) are analyzed. And compared with the theoretical value, increase the reliability of the finite element simulation results.

2. Finite element model establishment

2.1. Material parameter input
(1) The steel is made of Q235. The volume of H-shaped steel is 300mm*300mm*18mm*24mm, the yield strength is 235Mpa, the Poisson's ratio is 0.3, the elastic modulus is 210Gpa, and the tangential modulus is 21Gpa.
(2) Wood: The test uses Korean pine and glulam, both of which are anisotropic materials. The linear elastic parameters of the materials are based on the experimental data in [5], as shown in Table 1 below:

| Number | \(E_L\) (Mpa) | \(E_R\) (Mpa) | \(E_T\) (Mpa) | \(\mu_{RT}\) | \(\mu_{LR}\) | \(\mu_{LT}\) | \(G_{RT}\) (Mpa) | \(G_{LR}\) (Mpa) | \(G_{LT}\) (Mpa) |
|--------|---------------|---------------|---------------|-------------|-------------|-------------|---------------|---------------|---------------|
| Korean pine | 13743 | 434 | 434 | 0.341 | 0.341 | 0.528 | 935 | 765 | 935 |
| Glued wood | 10000 | 497.51 | 497.51 | 0.337 | 0.337 | 0.372 | 675 | 675 | 675 |

Note: The yield strength of glulam is 25Mpa, the tangent modulus is 2.5Mpa, and the density of Korean pine is 0.42g/cm³.

(3) Bolt: 30mm bolt is used, and the bolt strength grade is 10.9.

2.2. Test design

This test design 6 sets of test pieces, Table 2 is the sample parameter table: where L1, L2, L3 are the influence of bolt margin on the joint connection when the wood is all red pine; L4, L5, L6 are when the wood is glulam, the influence of bolt margin on the joint connection; when L1, L4 are 45mm, the influence of wood characteristics on the joint connection; L2, L5 when the bolt margin is 52.5mm, the influence of wood characteristics on the joint connection; L3, L6 when the bolt margin is 60mm, the influence of wood characteristics on the joint connection.

| Number | H-beam length (mm) | Board size (mm) | Wood properties (Mpa) | Bolt margin (mm) | Bolt diameter (mm) |
|--------|--------------------|-----------------|-----------------------|-----------------|-------------------|
| L1     | 1500               | 1500*300*150    | Korean pine           | 45              | 30                |
| L2     | 1500               | 1500*300*150    | Korean pine           | 52.5            | 30                |
| L3     | 1500               | 1500*300*150    | Korean pine           | 60              | 30                |
| L4     | 1500               | 1500*300*150    | Glued wood            | 45              | 30                |
| L5     | 1500               | 1500*300*150    | Glued wood            | 52.5            | 30                |
| L6     | 1500               | 1500*300*150    | Glued wood            | 60              | 30                |

2.3. Modeling method and unit selection

This experiment uses the method of symmetrical analysis, using the workbench software to make the model. The default unit used is solid186, and only 1/4 of the model is used, which facilitates the subsequent calculations to save computational complexity, making the results of the model calculation highly symmetrical. The constitutive model of the steel adopts a bilinear equivalent strengthening model.

Using 3D solid modeling, the model is shown in Figure 1. The width direction is the X direction, the length direction is the Y direction, and the thickness direction is the Z direction. All the freedom is constrained at the bottom of the test piece.
3. Analysis settings

3.1. Contact and loading method
There are five types of contact surfaces:

(1) The contact between the wood and the steel plate is due to the large difference in stiffness between the two, the H-shaped steel with high rigidity is taken as the target surface, the wood with low rigidity is used as the contact surface, and the asymmetric contact is adopted, and the friction coefficient is 0.1.

(2) The contact between the bolt column and the steel plate, both of which are Q235 steel, directly adopts symmetrical contact and is easy to converge.

(3) The contact between the nut and the steel has a small difference in stiffness and uses symmetrical contact.

(4) The contact between the nut and the wood board has a large difference in stiffness. The asymmetric contact is used, the bolt is used as the target surface, and the wood board is used as the contact surface.

(5) The contact between the bolt column and the wood hole has a large difference in stiffness. The asymmetric contact is adopted, the bolt is used as the target surface, and the wood board is used as the contact surface.

The loading method is applying a load of 250KN downward to the top of the 1/4 model, and the current load step end time is 1000s, that is, loading 1000KN within 1000s.

3.2. Meshing
For the bolt, that is, the edge portion of the contact surface adopts a 10 mm mesh, and the non-contact surface edge adopts a 40 mm mesh, which can greatly reduce the number of nodes, can simplify the calculation process, and make the calculation result more accurate.

4. Numerical simulation results

4.1. Load-displacement curve
Figure 2 shows the load-displacement curves of the six groups of tests. The horizontal axis is the displacement and the vertical axis represents the load. It can be seen from the figure that the curve is smooth and the node is actually in the initial stage of loading. The force loading is not enough, the displacement is not obvious, because the time is proportional to the load, at the beginning, the time does not move, so the load does not change, only a slight displacement. Because the grid has a discrete effect, there is a gap with the bolt hole, there is no displacement without applying pressure, and then the load is increased, and the displacement is also greatly increased.
The woods of the L1, L2, and L3 groups are all red pine, and the bolt margins are 45 mm, 52.5 mm, and 60 mm, respectively. In the elastic phase, as the bolt margin increases, the corresponding load increment decreases as the same displacement increases.

The wood of L4, L5 and L6 groups are all glued wood, and the bolt margins are 45mm, 52.5mm, 60 mm, respectively. In the elastic phase, as the bolt and bolt margin increases, the corresponding load increment increases as the same displacement increases.

The bolts of the L1 and L4 groups are all 45mm. The wood is made of Korean pine and glulam. In the elastic phase, when the same displacement is increased, the corresponding load increment is reduced.

The bolt spacing of L2 and L5 groups is 52.5mm, and the wood is taken from red pine and glulam. In the elastic phase, when the same displacement is increased, the corresponding load increment is unchanged.

The bolts of the L3 and L6 groups are all 60mm. The wood is made of Korean pine and glulam. In the elastic phase, when the same displacement is increased, the corresponding load increment is unchanged.

![Image of Load displacement curve](image)

**Figure 2.** Load displacement curve

4.2. **Stress cloud**

From the figure 3, it can be seen that the wood is an anisotropic material with a large elastic modulus in the longitudinal direction of the fiber, mainly by the length of the fiber supporting the bolt, and the transverse fiber is weak. The inner side of the bolt on the wood has large stress and the upper stress is small; the upper side has large stress and the lower stress is small because the H-beam is pressed downward, the bolt is pressed downward, the lower stress is large, and the upper stress is small; the outer side of the bolt The bolt head is pressed upwards, the upper stress is large, and the stress below is small.
4.3. Load capacity analysis

According to the American Wood Structure Design Specification NDS [6], the yield strength of the multi-bolt joint specimen is taken as the load value at the intersection of the horizontal offset line of the initial stiffness of 5\% d (d is the bolt diameter) and the load-displacement curve. ASTM D 176 [7] stipulated that the maximum deformation of the pin node in the test does not exceed 15mm. This paper only explores the damage of the bolt joint in 1000KN, and the deformation does not exceed 6mm, so the ultimate bearing capacity is 1000KN. The method of yield strength and ultimate load in the paper by Chao Fang [8] is shown in Figure 4 below:

5. Numerical simulation results compared with theoretical values

5.1. Calculation of bolt bearing capacity by "wood structure design code"

The "Code for Design of Wood Structures" (GB-50005-2003) [9] stipulates that the design bearing capacity of each shear plane of a single bolt connection is determined as a formula (1).

\[
N_V = K_V d^2 \sqrt{f_c}
\]  

(1)

| Numble | Yield strength (KN) | Ultimate strength (KN) | Initial stiffness (KN/mm) |
|--------|---------------------|------------------------|--------------------------|
| L_1    | 956.63              | 1000                   | 543.48                   |
| L_2    | 776.13              | 1000                   | 403.23                   |
| L_3    | 776.13              | 1000                   | 403.23                   |
| L_4    | 865.63              | 1000                   | 304.88                   |
| L_6    | 776.13              | 1000                   | 403.23                   |
| L_6    | 776.13              | 1000                   | 403.23                   |

Figure 3. Equivalent stress map of wood

Figure 4. Method for determining yield strength and ultimate load

The static analysis results of the test pieces of the joint test are as follows:

Table 3. Carrying capacity finite element analysis results
Wherein, $N_V$ the bearing capacity design value (KN) of each shear surface of the bolt
$K_V$ Bearing capacity coefficient of bolt connection, check the table, the value is 5
$d$ Bolt diameter, take 30mm
$f_{c}$ Wood design value of compressive bearing capacity (MPA)

From the above formula, it can be seen that when the bolt diameter and the bearing capacity coefficient are constant, the bolt bearing capacity is only related to the design value of the grain compressive bearing capacity of the wood. According to the test results of Jia You [10], the design value of the bearing capacity of Pinus koraiensis is 26.21-30.21 MPA, and the value of this paper is 27 MPA. According to the technical specification of the glulam structure [11], the design value of the bearing capacity of the glulam TCT24 is 14.8MPA.

5.2. Numerical simulation results and calculated values

The finite element simulation results and the theoretical value results are as shown in Table 4. The 5% yield strength is 1.04-1.6 times larger than the value of the wood structure design specification. The Chinese wood structure design specification has a certain conservative estimation range, so the finite element the simulation results are relatively reasonable.

Table 4. Comparison table between finite element simulation results and theoretical value results

| Number | 5% Yield load (KN) | Ultimate load (KN) | Wood structure specification (KN/mm) |
|--------|-------------------|--------------------|--------------------------------------|
| L₁     | 956.63            | 1000               | 739.43                               |
| L₂     | 776.13            | 1000               | 739.43                               |
| L₃     | 776.13            | 1000               | 739.43                               |
| L₄     | 865.63            | 1000               | 547.49                               |
| L₅     | 776.13            | 1000               | 547.49                               |
| L₆     | 776.13            | 1000               | 547.49                               |

6. Conclusion

In this paper, the bearing capacity of the pine and glulam at 45mm, 52.5mm and 60mm bolt margins is studied and compared with the theoretical value. The following conclusions were drawn:

1. The wood mainly supports the bolts in the direction of the longitudinal fibers.
2. The yield strength of Pinus koraiensis decreases with the increase of bolt margin; the yield strength of glulam decreases with the increase of bolt margin. At a bolt margin of 45 mm, the yield strength of Korean pine is greater than that of glulam. At 52.5 mm and 60 mm bolt margins, wood properties have little effect on yield strength.
3. The ultimate strength has little effect on bolt margins and wood properties.
4. The initial stiffness of Korean pine decreases with the increase of bolt margin; the initial stiffness of cemented wood increases with the increase of bolt margin. At a bolt margin of 45 mm, the initial stiffness of the pine is greater than that of the glulam. At 52.5 mm and 60 mm bolt margins, wood properties have little effect on initial stiffness.

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