Study on geometric optimization for new type of steel mortise and tenon joint based on performance

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Abstract. Mortise and tenon joint is a common connection way of ancient Chinese timber structure. On this basis, in order to explore for a new type of mortise and tenon joint suitable for steel structure, the finite element model of a new type of steel mortise and tenon joint was established to simulate the whole behavior of it under tensile force and bending moment by using ABAQUS software. In this way, the effects of tenon number, tenon height and tenon width on the maximum local Mises stress, area of plastic stress region, tensile and flexural properties were discussed. The results show that the maximum local Mises stress, area of plastic stress region, tensile and flexural properties of the new steel mortise and tenon joint are significantly affected by the tenon number and height, while the tenon width has little effect on these properties. When the tenon number is 4, the tenon height is 15mm, and the tenon width is 5mm, the new steel mortise and tenon joint has the best mechanical performance, and the steel consumption is relatively lower.

1. Introduction

The joint form is very important for steel structures. The steel structure transmits force through the joints, so the strength and stiffness of the joints will affect the overall stability, strength and other aspects of the structure. In the past, the joints of frame structure were divided into two types containing fully articulated joints which could not transmit bending moment and fully rigid joints which could transmit bending moment when designing a steel structure joint. In practical engineering, these two kinds of joints do not exist, and the joints in reality are semi-rigid.

Mortise and tenon joint is a connection mode combining concave and convex parts on two components. It is mainly used in ancient timber structures and plays an irreplaceable role in the connection mode of ancient Chinese architecture, furniture and various instruments. Based on mortise and tenon joints, a new joint mode of steel structure can be explored, that is, a new type of steel mortise and tenon joint. More accurate analysis can be made by studying the new type of steel mortise and tenon joint from the view of semi-rigid. Li et al.[1-3] took the practical engineering as an example to illustrate the structural mechanism, mechanical characteristics, advantages and disadvantages of various mortise and tenon joints in timber structures. Hu et al.[4-5] studied the stiffness value of mortise and tenon joints in ancient buildings, derived the deflection curve equation of wooden beam and pile, and obtained the stiffness value of the mortise and tenon joint suitable for timber structure in ancient buildings by using spring element to simulate the constraint of mortise and tenon joints. ANSYS finite
element model was also established to compare with the actual project. Duan et al.\cite{6-7} proposed a frame structure assembled by square steel tube by mortise and tenon joints, carried out the model test to study the mechanical performance of plane frames in the two directions, and determined that the frame structure belongs to the semi-rigid connection frame. Liu et al.\cite{8-11} from Tianjin University studied the bearing capacity and mechanical behavior of more than ten sets of full supported systems assembled with mortise and tenon joints by experiments. By using ANSYS software, the corresponding finite element model was established to discuss the influence of the geometric dimensions, such as the distance between the bars, and the length of the scissor support, and the components on the bearing capacity of the support system. Xue et al.\cite{12} introduced the structure of steel pipe scaffold assembled by mortise and tenon joint and it with the other forms of steel pipe scaffold. Finally, they concluded that the steel pipe scaffold assembled by mortise and tenon joints has certain application value and prospect and it is worthy of further research. Xu et al.\cite{13-16} studied the seismic performance of a single-storey steel house integrated by mortise and tenon joints through experiments, proved that the steel mortise and tenon joint has high strength and reliable connection, the overall structure has better seismic capability, and it can be used in high earthquake intensity area. The scholars mentioned above have studied the structural mechanism and mechanical properties of the mortise and tenon joint in timber structures, and discussed the application of mortise and tenon joints in temporary steel supports and frames. Obviously, there are few research data on steel mortise and tenon joints, and it is urgent to study the optimal structure form, reasonable geometric dimensions and mechanical properties under various loads.

In this paper, the mechanical performance of a new type of steel mortise and tenon joint with different sizes will be discussed based on the finite element simulation analysis of ABAQUS. By comparing their tensile behavior and flexural behavior, the dimensions of the new type of steel mortise and tenon joint will be optimized.

2. Finite Element Model

2.1. The basic structure

The new steel mortise and tenon joint mainly consists of internal steel pipe and external casing pipe. Figure 1 presents the specific section and structure. In figure 1, a stands for the inner wall radius of the internal steel pipe, b stands for the outer wall radius of the internal steel pipe including the thickness of the tenon, c stands for the outer wall radius of the internal steel pipe without the thickness of the tenon, g stands for the tenon height of the internal steel pipe, j stands for the distance between the mortise and tenon layers of the internal steel pipe, m stands for the lining wall radius of the external casing pipe, n stands for the outer wall radius of the external casing pipe, and l stands for the inner wall radius of the external casing pipe.
2.2. Module assembly
Each part is assembled under the assembly module according to the relative position requirements of the entity. The internal steel pipe is inserted into the external casing pipe along the socket on the external casing pipe and rotated at a certain angle. Then the anti-rotation pin is inserted to complete the assembly. Since the anti-rotation pin does not involve the problem of force transmission, the finite element model of it was not established. The completed assembly model is shown in figure 2(a).

2.3. Parameter settings
The material behavior of steel was defined in the attribute module. The specific datas of the internal steel pipe properties are shown in table 1. When the steel pipe properties are determined, the external casing pipe is determined. The elastic model and the ideal elastic-plastic model were used for the numerical simulation. The interaction function module in ABAQUS/CAE is mainly used to define the mechanical interaction between various parts of the model. In this model, universal contacts were set to denote the effect. Meshing module is used to mesh models, and mesh parameters need to be set before mesh generation, and the rationality of the mesh is the necessary guarantee for its accurate calculation, and mesh parameters will change depending on different models. All the parts of the model were modeled by 3d entities, so the element type was C3D8R (eight-node linear hexahedral element). The model after meshing is shown in figure 2(b).

Table 1. Internal steel pipe properties

| Outer diameter (mm) | Wall thickness (mm) | Cross-sectional area (mm²) | Density (kg/m³) | Elasticity modulus (N/mm²) | Poisson's ratio | The yielding strength (MPa) |
|---------------------|--------------------|---------------------------|-----------------|---------------------------|----------------|--------------------------|
| 48                  | 3.5                | 4.89                      | 7850            | 2.06                      | 0.3            | 235                      |

Figure 2. Geometric model and finite element model
2.4. Load case
In this paper, the geometric optimization of the new type of steel mortise and tenon joint based on the performance was studied. The resistances to tension and bending were used as the criterion of the mechanical properties of the joint.

When studying the resistance to tension of the joint, the same axial tension should be applied to the end points of the model with different structural forms and geometric dimensions under the condition that one end was fully fixed supported. In order to determine the value of this axial tension, the calculations of the external casing pipe and internal steel pipe under axial tension were conducted, respectively. By increasing the axial tension exerted on the end of the external casing pipe and the internal steel pipe, the ultimate axial tensile bearing capacities of them were obtained. Moreover, the ultimate tensile bearing capacity of the external casing pipe is about 102.4kN, and it is less than the ultimate bearing capacity of the internal steel pipe. And the ultimate tensile bearing capacity of the above model after assembly is greater than that of the external casing pipe alone. Moreover, when the assembled model was applied with the axial tension of 102.4kN, plastic stress region exists in both the external casing pipe and the internal steel pipe. Therefore, the value of the axial tension applied to the end points of the joint model is elected as 102.4kN, which can better reflect the performance of the model under axial tension. This axial tension was then gradually increased until the joint model reached its ultimate tensile bearing capacity.

When studying the resistance to bending of the joint, the same concentrated force perpendicular to the axis of the joint model was applied to the end points of the joint model with different structural forms and geometric dimensions under the condition that one end was fully fixed supported. When the concentrated force of 3kN was applied to the model, plastic stress region exists in both the external casing pipe and the internal steel pipe. Therefore, the value of the concentrated force applied on the endpoint of the joint model was elected as 3kN, which can better reflect the performance of the joint model under bending moment. This concentrated force was then gradually increased until the joint model reached its ultimate flexural bearing capacity.

3. Results and Analysis

3.1. The influence of the number of tenon on the mechanical performance of the new steel mortise and tenon joint

3.1.1. Influence on the tensile property. The geometric models and finite element models with different number of tenon were established. There were two layers of tenon on each internal steel pipe, the height of tenon were 15mm and the distance between the layers was 10mm. Model 1 (N-2) had 2 tenons per layer, Model 2 (N-3) had 3 tenons per layer, Model 3 (n-4) had 4 tenons per layer, Model 4 (n-5) had 5 tenons per layer, Model 5 (N-6) had 6 tenons per layer, Model 6 (N-7) had 8 tenons per layer, and Model 7 (N-8) had 10 tenons per layer. One end of the internal steel pipe was fully fixed supported, and the other end was applied with the axial tension of 102.4kN. Local Mises stresses were calculated and extracted as shown in figure 3, and the maximum Mises stress is shown in table 2.
Figure 3. Local Mises stress for the models with different number of tenon under tension

Table 2. The maximum Mises stress for models with different number of tenon under tension

| The model number | N-2    | N-3    | N-4    | N-5    | N-6    | N-8    | N-10   |
|------------------|--------|--------|--------|--------|--------|--------|--------|
| The maximum stress /MPa | 429.3  | 334.9  | 301.6  | 292.6  | 287    | 280.3  | 275.1  |

The gray region in figure 3 indicates that the Mises stress of this region exceeds 235MPa, and it means this region is a plastic stress region. From figure 3, we can see that with the increase of the number of tenon, the plastic stress region area decreases gradually. From the data in table 2, we found that the maximum Mises stress decreases with the increase of the number of tenon. The maximum Mises stress varied significantly when the number of tenon is less than or equal to 3, while it varied little when the number of tenon is greater than 3.

Figure 4. Load-displacement curve for models with different number of tenon under tension

After that, the axial tension keeps increasing until the joint model reaches its ultimate tensile bearing capacity. In this process, the load-displacement curves calculated by each model are shown in figure4. It can be found that the ultimate tensile bearing capacity of N-2 is 97.3kN, the ultimate flexural bearing capacity of N-3 to N-10 varies little, and it is about 117.8kN. The results show that the maximum Mises stress of the joint model decreases with the increase of the number of tenon under
the same load. When the number of tenon exceeds 3, the ultimate tensile bearing capacity is approximately the same.

3.1.2. Influence on the flexural behavior. In order to study the influence of the number of tenons on the flexural behavior of the joint, the model in section 3.1.1 was used for the following finite element calculation. The fully fixed support was adopted at one end of the internal steel pipe, and the load was applied in two steps. In the first step, the concentrated force of 3kN perpendicular to the axial direction of the joint model was loaded at the pipe head. And the displacement of the pipe head was obtained when the model was destroyed. In the second step, the load was changed from the concentrated force to a forced displacement in the same direction as the concentrated force applied before. The value of the forced displacement is the same as the displacement obtained in the first step when the model was destroyed before. The local Mises stress cloud map was calculated and extracted as shown in figure 5. The maximum Mises stress is shown in table 3.

![Local Mises stress for the models with different numbers of tenon under bending moment](image)

Table 3. The maximum Mises stress for the models with different numbers of tenon under bending moment

| The model number | N-2  | N-3  | N-4  | N-5  | N-6  | N-8  | N-10 |
|------------------|------|------|------|------|------|------|------|
| The maximum stress /MPa | 329.4 | 376.1 | 362.6 | 346.8 | 338.4 | 324.7 | 318.5 |

It can be seen from figure 5 that, by comparing the plastic stress region area of the joint models, it can be found that the plastic stress region of the N-4 model has the smallest area. When the number of tenon exceeds 4, the gray area gradually increases. It shows that the plastic stress region of N-4 model is the smallest when the same load is applied. According to table 3, the maximum Mises stress for models with different number of tenon is above 300MPa, which varies little to each other.
Figure 6. Bending moment-angle curve for the models with different number of tenon under bending moment

After that, the bending moment keeps increasing until the model reaches its ultimate flexural bearing capacity. In this process, the bending moment-angle curve calculated by each model is shown in figure 6. It can be seen that the ultimate flexural bearing capacities of model N-2 and N-3 are smaller, which are 1687N·m and 1728.26N·m, and the ultimate flexural bearing capacities of the other six models vary little, which are all about 1775N·m.

According to the research above, whether the model is under tension or bending moment, as the number of the tenons trends to increase, the ultimate bearing capacity trends to increase, the maximum Mises stress and the plastic stress region area overall trends to decrease gradually, this is because as the number of the tenons increases, the contact area of the internal steel pipe and the external casing pipe increases, the tangential and radial transmission force trend to be more uniform, the maximum Mises stress and the plastic stress region area trend to decrease, the ultimate flexural bearing capacity and the ultimate tensile bearing capacity accordingly increase. When the number of tenon is greater than 3, the maximum Mises stress is smaller under bending moment, the ultimate flexural bearing capacity is higher, and the maximum Mises stress and ultimate flexural bearing capacities were not significantly affected by the increase of the number of tenon. When the number of tenon in each layer is 4, the plastic stress region area of the model is the smallest, when the number of tenons is greater than 4, the ultimate flexural bearing capacity, the ultimate tensile bearing capacity, the maximum Mises stress and plastic stress region area of the models change little.

Considering the factors above, the number of tenon is chosen as 4. In this way, the maximum Mises stress is both smaller under tensile force and bending moment, the ultimate tensile bearing capacity is higher, the plastic stress region area is the smallest, and the mechanical properties are better under the condition of lower steel consumption.

3.2. The influence of the height of tenon on the mechanical properties of the new steel mortise and tenon joint

3.2.1. Influence on the tensile property. According to the research above, when the number of tenon is 4, the joint model has a better mechanical performance. The following discussion will only discuss the mechanical performance of the new type of steel mortise and tenon joint with the number of tenon 4.
The geometric model and finite element model with different tenon height were established. According to the study above, there were two layers of tenon on each internal steel pipe, the number of tenon in each layer on each internal steel pipe was 4, and the distance between the two layers were 10mm. The height of the tenon of model 1 (G-5) is 5mm, that of model 2 (G-10) was 10mm, that of Model 3 (G-15) was 15mm, and that of model 4 (G-20) was 20mm. With one end fully fixed supported, the axial tension of 102.4kN was applied on the other end. The local Mises stress cloud map was calculated and extracted as shown in figure 7, and the maximum Mises stress is shown in table 4.

![Local Mises stress of G-5](image1)
![Local Mises stress of G-10](image2)
![Local Mises stress of G-15](image3)
![Local Mises stress of G-20](image4)

Figure 7. Local Mises stress for the model with different height of tenon under tension

Table 4. The maximum Mises stress for the model with different height of tenon under tension

| The model number | G-5   | G-10  | G-15  | G-20  |
|------------------|-------|-------|-------|-------|
| The maximum stress /MPa | 449.4 | 392.2 | 300.2 | 293.7 |

According to the comparison based on figure 7 and table 4, the maximum Mises stress of G-20 is the lowest, and the maximum Mises stress of the four models decreases with the increase of tenon height. By comparing the region area where the stress is over 235MPa, it can be found that the grey area of the four models decreases gradually, but the change tends to be flat after the tenon height exceeds 10mm.

![Load-displacement curve for the models with different tenon height under tension](image5)
After that, the axial tension kept increasing until the model reaches its ultimate tensile bearing capacity. In this process, the load-displacement curve of the model applied with the tension force is shown in figure 8. It can be concluded that the ultimate tensile bearing capacity of model G-5 is smaller which is about 60kN. The ultimate tensile bearing capacities of the remaining three models are about 100kN.

3.2.2. Influence on the flexural behavior. In order to study the effect of tenon height on the joint model flexural behavior, the same model as that in section 3.2.1 was adopted. The load and forced displacement were applied in the same way as that in section 3.1.2. The local Mises stress cloud map was calculated and extracted as shown in figure 9. The maximum Mises stress is shown in table 5.

![Figure 9. Local Mises stress for the model with different height of tenon under bending moment](image)

![Table 5. The maximum Mises stress for the model with different height of tenon under bending moment](table)

According to the comparison based on figure 9 and table 5, the maximum Mises stress of G-20 is the lowest, and the maximum Mises stress of the four models is close to each other. By comparing the region area where the value of the stress is over 235MPa, it can be found that the area decreases gradually from G-5 to G-20.

![Figure 10. Bending moment-angle curve for the model with different height of tenon under bending moment](image)

After that, the concentrated force kept increasing until the model reached its ultimate flexural bearing capacity. In this process, the bending moment-angle curve calculated by each model during bending is shown in figure 10. It can be seen that the ultimate flexural bearing capacity of model G-5 is smaller, which is about 1600N·m; the ultimate flexural bearing capacities of the other six models
vary little, which are all about 1800N·m; the ultimate flexural bearing capacities of G-5 to G-20 gradually increase. According to the research above, whether the model is under tension or bending moment, as the height of the tenons increases, the ultimate bearing capacity trends to increase, the maximum Mises stress and the plastic stress region area trend to decrease gradually, this is because as the height of the tenons increases, the contact area of the internal steel pipe and the external casing pipe increases, the tangential and radial transmission force trend to be more uniform, the maximum Mises stress and the plastic stress region area overall trends to decrease, the ultimate flexural bearing capacity and the ultimate tensile bearing capacity accordingly increase. When the tenon height is more than 10 mm, the plastic stress region area changes slightly in the model, the ultimate tensile bearing capacity of the model is larger. And the increase of the height of the tenon would not influence the plastic stress region area and the ultimate tensile bearing capacity of the model greatly. When the tenon height is more than 10mm, the maximum Mises stress of the model under bending moment is significantly smaller, the ultimate flexural bearing capacity of the model is larger, and the increase of the height of the tenon would not influence the maximum Mises stress and the ultimate flexural bearing capacity of the model greatly. When the height of tenon is 15mm, the plastic stress region area of the model is the smallest, when the height of tenons is greater than 15mm, the ultimate flexural bearing capacity, the ultimate tensile bearing capacity, the maximum Mises stress and plastic stress region area of the models change little.

Considering the factors above, it can be obtained that when the tenon height is 15mm, the ultimate tensile and flexural bearing capacity of the model are both higher, and the plastic stress region area of the model is smaller when the same displacement is applied to the pipe head. Therefore, when the height of the tenon is 15mm, it can not only guarantee the smaller amount of steel consumption, but also guarantee a better mechanical performance of the joint model.

3.3. The influence of the width of tenon on the mechanical properties of the new steel mortise and tenon joint

3.3.1. Influence on the tensile property. According to the research above, the model has better mechanical performance when the number of tenon is 4 and the height of the tenon is 15mm. The following will only discuss the mechanical performance of the new type of steel mortise and tenon joint when the number of tenon is 4 and the height of tenon is 15mm.

The geometric model and finite element model with different tenon widths were established. There were two layers with four tenons in each layer on the internal steel pipe, the distance between two layers were 10mm, and the height of each tenon was 10mm. The tenon width of model 1 (K-4) was 4mm, that of model 2 (K-5) was 5mm, that of model 3 (K-6) was 6mm, that of model 4 (K-7) was 7mm, and that of model 5 (K-8) was 8mm. With one end fully fixed supported, the axial tension of 102.4kN was applied on the other end. The local Mises stress cloud map was calculated and extracted as shown in figure 11, and the maximum Mises stress is shown in table 6.

![Figure 11. Local Mises stress for the models with different width of tenon under tension](image-url)
Table 6. The maximum Mises stress for the model with different width of tenon under tension

| The model number | K-4   | K-5   | K-6   | K-7   | K-8   |
|------------------|-------|-------|-------|-------|-------|
| The maximum stress /MPa | 344.1 | 392.2 | 396.4 | 418.1 | 445.0 |

According to the comparison based on figure 11 and table 6, the maximum Mises stress of model K-4 is the lowest, and the maximum Mises stress of the five models increases with the increase of tenon width. By comparing the area where the stress is above 235MPa, it can be found that the gray area of the five models gradually increases. The reason is that with the increase of the tenon width, the bending moment at the root of the tenon becomes larger and larger, which makes the stress at the wall of the steel pipe connected with the tenon increase.

Figure 12. Load-displacement curve for models with different tenon width under tension

After that, the axial tension kept increasing until the model reaches its ultimate tensile bearing capacity. In this process, the load-displacement curve calculated by each model under tension is shown in figure 12. It can be seen that the ultimate tensile bearing capacities of the five models are very close, which are about 115kN. It shows that the tenon width has little influence on the tensile property of the joint models.

3.3.2. Influence on the flexural behavior.

In order to study the effect of tenon width on the flexural behavior of the joint, the same model as that in section 3.3.1 was adopted. The load and forced displacement were applied in the same way as that in section 3.1.2. The local Mises stress cloud map was calculated and extracted as shown in figure 13. The maximum Mises stress is shown in table 7.

Table 7. The maximum Mises stress for models with different width of tenon under bending moment

| The model number | K-4   | K-5   | K-6   | K-7   | K-8   |
|------------------|-------|-------|-------|-------|-------|
| The maximum stress /MPa | 352.4 | 339.7 | 343.9 | 366.1 | 379.0 |

Figure 13. Local Mises stress for models with different width of tenon under bending moment
According to the comparison based on figure 13 and table 7, the maximum Mises stress of K-5 is the lowest, and the maximum Mises stress of the five models is close to each other. By comparing the region area where the value of the stress is over 235 MPa, it can be found that the plastic stress region area varies little.

After that, the concentrated force kept increasing until the model reached its ultimate flexural bearing capacity. In this process, the bending moment-angle curve calculated by each model is shown in figure 14. It can be seen that the ultimate flexural bearing capacities of the models are basically the same which are all about 1800 N·m.

According to the results above, it can be concluded that as the width of the tenon increases, the maximum Mises stress of the model applied with tension increases gradually, while the plastic stress region area changes little, and the ultimate tensile bearing capacities trends to decrease gradually in general and changes little. The maximum Mises stress of the model is the lowest when the tenon is under bending moment with the width 5 mm. With the increase of tenon width, the maximum Mises stress of the model under bending moment increased gradually with a small range, the plastic stress region area trends to increase gradually with a small range too. The general trend of the ultimate tensile bearing capacity of the model is to decrease gradually with a small range. This is because the larger the width of the mortise and tenon, the larger the stretching distance of the tenons, and the greater the bending moment and shear force at the root of the tenons under stress, which results in the decrease of the model's bearing capacity performance. When the tenon width is 4 mm, the stress area is too small and the stress performance is poor. But in general, the maximum Mises stress, ultimate flexural bearing capacity and plastic stress region of the model are not significantly affected by the changes of tenon width. Therefore, it is considered that when the tenon width is 5 mm, a smaller amount of steel consumption can be guaranteed, and the mechanical performance of the joint model is relatively good.

4. Conclusions
In this paper, the new steel mortise and tenon joints with different geometric dimensions were compared by the tensile property and flexural behavior, and the conclusions are drawn as follow:

(1) The new steel mortise and tenon joint is composed of internal steel pipe and external casing pipe. The internal steel pipe is inserted into the external casing pipe along the socket of the external
casing pipe and rotated at a certain angle, and the anti-rotation pin is inserted to complete the assembly. The joint can transfer tension and bending moment, and its mechanical performance is related to the number, height and width of the tenon;

(2) The calculations of seven kinds of joints with the different number of tenons, four kinds of joints with different tenon heights, five kinds of joints with different tenon widths under tension and bending moment were conducted. And the local maximum Mises stress, ultimate tensile and bending bearing capacity and plastic stress region of the models were used to evaluate the mechanical properties of the models. The results show that as the local maximum Mises stress gets smaller, the ultimate tensile and flexural bearing capacities get larger, the plastic stress region area gets smaller. That means the model has a better mechanical performance. As the local maximum Mises stress gets larger, the ultimate tensile and bending bearing capacities get smaller, the plastic stress region area gets larger. That means the model has a poor mechanical performance.

(3) In order to ensure that the new type of steel mortise and tenon joint can have the best mechanical performance under the condition of the minimum amount of steel consumption, it is suggested to select the tenon number as 4, the tenon height as 15mm and the tenon width as 5mm.

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