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Comparative Study on the Beam Structure of Traditional Houses in Pingjiang Area Based on Finite Element Analysis

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Abstract: *The traditional houses in Pingjiang area have important conservation value due to their unique regional characteristics and cultural features. This paper summarizes the architectural characteristics of different beam structures in the area based on field survey, and uses the finite element method to carry out experimental simulation and theoretical analysis of the combination of the frontal post and lintel construction and the side wall shelf purlin construction, and the combination of the frontal post and lintel construction and the side column and tie construction, so as to compare the mechanical properties of different beam structures. The research results show that the structure of the combination of the frontal post and lintel construction and the side column and tie construction is more stable. The article can provide a scientific and theoretical basis for the conservation and design of traditional houses.*

Keywords: ***t****raditional houses; beam structure; finite element analysis method; mechanical properties*

1. Introduction

As a representative of traditional Chinese architectural culture, traditional houses have strong regional characteristics, and the special beam structure reflects the technology of the past [1]. The beam structure is the main part of the building, which generally consists of a combination of wooden elements such as columns, beams, strips and purlins. Whether it is the post and lintel type of construction, the column and tie type of construction, or the side wall shelf purlin type of construction, the interplay of various practices creates a complex beam structure.

In Pingjiang area, the combination of the frontal post and lintel construction and the side wall shelf purlin construction, and the combination of the frontal post and lintel construction and the side column and tie construction are two common types of beam construction, which are mainly found in gate houses, ancestral halls, horizontal halls, and some compartments. The spans between the walls of these houses are generally small, typically 3.6-4metres, with 150-180mm diameter purlins inserted into the side load bearing structures.

1.1 Combination of the frontal post and lintel construction and the side wall shelf purlin construction

In traditional houses in Pingjiang area, the length of the timber can often be the same as the span of the room. Therefore, it is common in this area for halls to have the post and lintel construction at the front and the wall shelf purlin construction at the side (see Fig.1). This means that at the front of the hall two large beams are used to support the five-frame beams, on the five-frame beams the three-frame beams are supported by humps, and on the three-frame beams the purlins are supported by humps. At the sides, the large beams are usually inserted into the wall together with the purlins, thus creating a regional architectural practice [2].

1.2 Combination of the frontal post and lintel construction and the side column and tie construction

Due to the small amount of space available in traditional Chinese architecture, it is also common in traditional houses in the Pingjiang area to use the post and lintel construction at the front of the hall and the side column and tie construction at the side of the hall (see Fig 2). The common local practice is that at the front of the hall, two large beams are used to support the five-frame beams, the five-frame beams are used to support the three-frame beams through the hump, and the three-frame beams are used to

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support the purlins through the hump. At the sides, the large beams are usually inserted with the purlins into the column and tie construction [3].

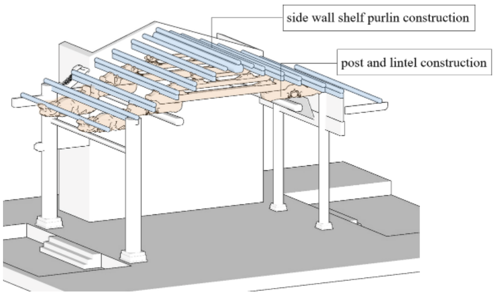

Fig. 1: The model of type 1

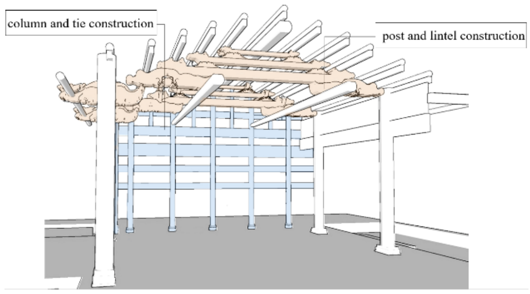

Fig. 2: The model of type 2

2. Method

The wooden frame of the Kanliang House in Tangpu Village, Nanjiang Town, and the Shanxia House in Yangsi Village, Changshou Town, were used as the objects of finite element analysis in this paper, and ANSYS simulation was introduced to find the weak parts of the beam structure through static analysis [4].

In the building structure, timber members such as beams and columns have different cross-sectional shapes and are affected by shear deformation, so Beam189 unit was selected to customize the cross-sectional shape of the beams in this way, and transverse section (TR), radius section (LT) and chord section (LR) were selected for force analysis[5]. In addition, most of the wooden members are connected by mortise and tenon, which cannot overcome the deformation between them and may twist and rotate under the load. Therefore, the article adopts the Combin14 unit to set up the axial and torsional spring units for simulation. The approximate spring stiffness of the mortise and tenon nodes is obtained by analysis and calculation based on previous studies as [6] : $K_x = 113.3\ \text{kN} \cdot m^{-1}, K_y = K_z = 127950\ \text{kN} \cdot m^{-1}, K_{xy} = K_{yz} = K_{zx} = 296.711(\text{ kN} \cdot m) \cdot rad^{-1}$.

2.1 Combination of the frontal post and lintel construction and the side wall shelf purlin construction

2.1.1 Basic dimensions of the model

The Kanliang House was built in the seventh year of the Qianlong's reign (1742), and the building is majestic. The room has a width of 4.3m and a depth of 6.71m, and the front hall is a post and lintel construction and the side hall is a wall shelf purlin construction. The cutaway view is shown in Fig.3. The dimensions of each wooden member in the chancel model have been slightly adjusted on the basis of field mapping (see Tab. 1).

Tab. 1: Main component dimensions of Kanliang House(mm)

component	dimensions	height
three-frame beam	250	250
five-frame beam	235	235
crest string	320	320
large beam	260	260
architrave	260	260
outer column	400	—
inner column	400	—
purlin	120	120
rafter	40	40

2.1.2 Determination the roof load

The weight of the roof is transferred to the rafters, which in turn transfer the load to the purlins, which in turn transfer the load to the beam structure and then to the ground [7]. The simplified calculation process is as follows:

Roof Layer load: $230.5kg/m^2$

Roof horizontal projection area: $A = 7.62 \times 10.64 = 81.08m^2$

Roof sloping area: $A_s = 5.1 \times 7.62 + 6.75 \times 7.62 = 90.3m^2$

Load values after conversion of snow load to sloped projection: $S_k = \mu_r \times S_0 = 0.5 \times 0.6 \times 0.45 \times \frac{90.3}{81.08} = 0.15kN/m^2$

The loading condition chosen in this paper is the sum of the self-weight and the snow load [8]. Therefore the total roof load is assumed to be $245.806kg/m^2$.

2.1.3 Displacement analysis under the action of static forces

When performing the analysis, two conditions are considered: Condition 1, without considering the reduction of wood frame elastic modulus, that is, simulating the conditions of the original state; Condition 2, referring to Qian Zhou's "Structural Analysis and Protection of Ancient Buildings in The Imperial Palace", taking into account factors such as wood ageing, decay, insect infestation, etc., set the wood frame elastic modulus reduction of 30% [4], that is, simulating the current conditions. Based on the field-mapped data, a 3D model was established (see Fig. 4), with the X-and Y-axes set as horizontal directions and the Z-axis as the vertical direction.

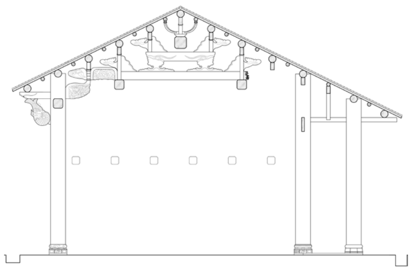

Fig 3: Cutaway view of Kangliang House

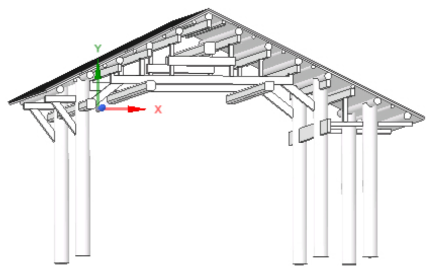

Fig 4: 3D model of Kangliang House

2.2 Combination of the frontal post and lintel construction and the side column and tie construction

2.2.1 Basic dimensions of the model

Shanxia House is located in Yangsi Village, Changshou Town, Pingjiang County, Yueyang City, Hunan Province, and is a representative building among many traditional Ming and Qing Dynasty houses in the village. The width of the room is 3.13 m and the depth is 9.2 m. The front hall is a post and lintel construction and the side hall is a column and tie construction, the cutaway view is shown in Fig.5. The dimensions of each wooden member in the chancel model have been slightly adjusted on the basis of field mapping (see Tab 2).

Tab 2: Main component dimensions of Shanxia House(mm)

component	dimensions	height
three-frame beam	300	300
five-frame beam	380	380
crest string	190	190
large beam	250	250
architrave	250	250
outer column	320	—
purlin	120	120
rafter	40	40

2.2.2 Determination the roof load

The weight of the roof is transferred to the rafters, which in turn transfer the load to the purlins, which in turn transfer the load to the beam frame and then to the ground [7]. The simplified calculation process is as follows:

Roof Layer load: $164.3kg/m^2$

Roof horizontal projection area: $A = 6.28 \times 9.2 = 57.776m^2$

Roof sloping area: $A_s = 5.2 \times 6.28 \times 2 = 65.312m^2$

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Load values after conversion of snow load to sloped projection: $S_k = \mu_r \times S_0 = 0.5 \times 0.6 \times 0.45 \times \frac{65.312}{57.776} = 0.15kN/m^2$

The loading condition chosen in this paper is the sum of the self-weight and the snow load [8]. Therefore the total roof load is assumed to be $179.606kg/m^2$

2.2.3 Displacement analysis under the action of static forces

This paragraph is analyzed in the same way as above, according to the data mapped in the field to establish a 3D model(see Figure 6), and set the horizontal for the X-axis direction, vertical for the Y-axis direction, and vertical for the Z-axis direction.

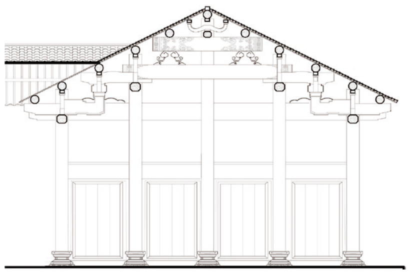

Fig 5: Cutaway view of Shanxia House

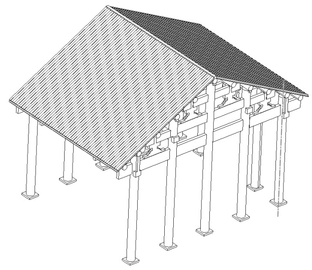

Fig 6: 3D model of Shanxia House

3. Result

3.1 Combination of the frontal post and lintel construction and the side wall shelf purlin construction

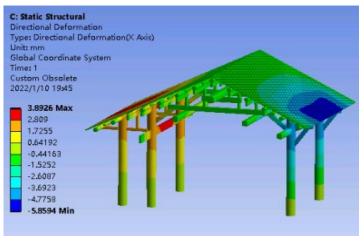

Fig 7: X-directional displacement

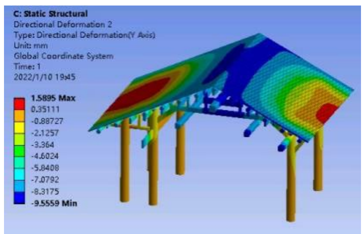

Fig 8: Y-directional displacement

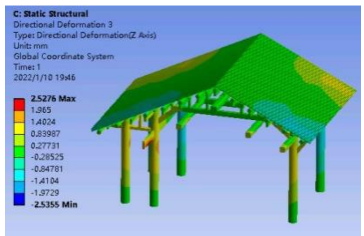

Fig 9:Z-directional displacement

(X,Y,Z displacement of Kangliang House)

3.1.1 Displacement in X-direction

From Fig 7 after loading, it can be seen that the maximum value of X-direction displacement occurs in the middle area of the outermost purlin on the left side of the beam frame. This is because the purlins are laterally subjected to the horizontal thrust of the rafters, and the deformation of the purlins is limited not only constrained by the connection between the purlins and the rafters, but also by the connection between the purlins and the beams. The depth of the back porch is greater than the width of the other span, and the force of the outermost purlin through the rafters is greater than that through the other purlins. Therefore, the X-direction displacement value of each purlin reaches its maximum from right to left towards the outermost purlin and has the tendency to roll outward. A wedge can be inserted into the groove at the end of the beam to secure the purlins.

3.1.2 Displacement in Y-direction

From Fig 8 after loading, it can be seen that the maximum value of Y-direction displacement occurs in the middle area of the outermost purlin on both sides of the beam structure, and the displacement values in the centre of other purlins are also greater. This is due to the fact that the rear roof is more heavily loaded than the front roof, and the pressure on the rear span is greater than that on the front span. The total displacement distribution of the structure is approximately circular, similar to the total displacement cloud. And from top to bottom, the vertical displacement of the beam structure becomes greater as the self-weight increases. Therefore, if the purlins are bent, sagging, etc., they can be replaced in time.

3.1.3 Displacement in Z-direction

From Fig 9 after loading, it can be seen that the maximum value of Z-direction displacement occurs on the column with a small value, and the overall difference of the beam frame is not significant. This is because the ends of the three-frame beams are supported by the humps on the five-frame beams, and the ends of the five frame beams are supported by the large beams. The load above the beam frame is transferred through the five-frame beams to the main beams and then to the columns on either side, so the displacement of the columns is greatest in the Z direction. If the columns of a truss become rotten due to moisture, the structure of the truss will tend to shift, causing the roof to collapse, which can be remedied by replacing the columns.

3.2 Combination of the frontal post and lintel construction and the side column and tie construction

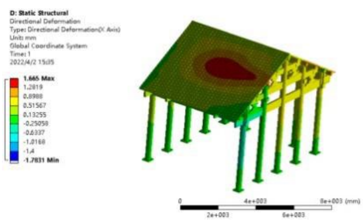
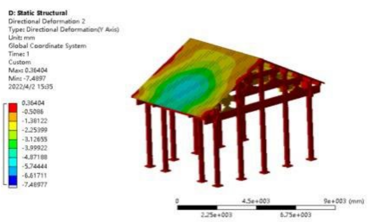
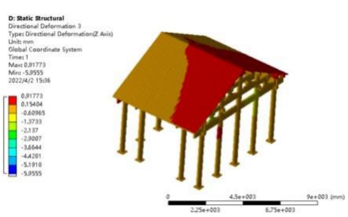

Fig 10: X-directional displacement   Fig 11: Y-directional displacement   Fig 12: Z-directional displacement

(X,Y,Z displacement of Shanxia House)

3.2.1 Displacement in X-direction

From Fig 10 after loading, it can be seen that the maximum value of X-direction displacement occurs in the middle area of purlin in the middle of the roof. This is because the purlins are laterally subjected to the horizontal thrust of the rafters, and the deformation of the purlins is not only limited by the connection between purlins and rafters and purlins and beams. The X-direction displacement value of each purlin gradually increases with height, reaching a maximum at the middle area of the middle purlin, and there is no tendency to roll outwards. However, if the purlins are bent, sagging, etc., they should be replaced immediately.

3.2.2 Displacement in Y-direction

From Fig 11 after loading, it can be seen that the maximum value of Y-direction displacement occurs in the area of the side beam frame. And from top to bottom, as the self-weight increases, the vertical displacement of the beam frame also becomes larger and larger. As the columns directly support the weight of the beam frame, any localized cracking or deterioration should be repaired if necessary.

3.2.3 Displacement in Z-direction

From Fig 12 after loading, it can be seen that the maximum value of displacement in the Z direction occurs in the area of the side beam frame. The larger value is due to the fact that the side beam frame takes the roof load transferred from the purlins and transfers it to the column frame, and the longitudinal direction of the beam frame is restrained by the purlins, large beam, through strip and other members to ensure the longitudinal stiffness of the structure. Only one side of the roof frame is restrained by the purlins and connecting strip, so it is more likely to deform than the frontal beam frame. If the column of the side beam frame is rotten due to the humid climate, it is easy to cause the beam frame structure to deflect and then cause the roof of the room to collapse, and then the structure can be corrected by replacing the column.

4. Discussion

Comparing the deformation of the two beam structures under the action of self-weight and the snow load in different directions, it can be seen that the deformation values of the combination of the frontal post and lintel construction and the side wall shelf purlin construction of the Kanliang House are generally large, indicating that its overall stability is weak. The deformation value of the combination of the frontal post and lintel construction and the side column and tie construction of the Shanxia House is generally small (see Tab 3).

Tab 3: Maximum displacement values of structures and their places

direction	Kanliang House			Shanxia House		
	Initial maximum displacement (mm)	Discounted maximum displacement (mm)	Place of appearance	Initial maximum displacement (mm)	Discounted maximum displacement (mm)	Place of appearance
X-directional	3.89	19.45	middle of outermost left purlin	1.67	8.33	middle of front middle purlin
Y-directional	1.59	7.95	middle of outermost purlin on both sides	0.36	1.82	side beam frame
Z-directional	2.53	12.65	front column	0.92	4.59	side beam frame

This is because, from a mechanical point of view, the concentrated load causes the beams to produce two sets of upward reactions to resist the downward deflection of the purlins, reducing the forces on the purlins here. Therefore, although the side column and tie construction differs from the side wall shelf purlin construction in that it is not supported by the wall below, it has little overall effect on the structural stability of the house. Especially, in the case of the Shanxia House, in the longitudinal direction, the beam frame adopts a triangular structure, forming a whole with the roof that is structurally strong and resilient. In addition, a number of timber strips run across the column body and a small number of timber strips carry the load transferred by the hump, which has the dual effect of tension and bending; in the horizontal direction, the purlins and main beams are inserted into the side column body, forming a vertical and horizontal support system which greatly enhances the integrity and reliability of the beam structure.

5. Conclusion

The article summarizes the architectural characteristics of the beam structure of the traditional houses in Pingjiang area, and selects the frames of the Kanliang House and the Shanxia House as the objects of finite element analysis, constructs a 3D model, and analyses the deformation characteristics of the frame structure using ANSYS. It is considered that the combination of the frontal post and lintel construction and the side column and tie construction is a more stable structure. In addition, the analysis found the weak points of the beam and column structure, hoping to provide a technical reference for the restoration of traditional houses.

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