

Numerical Analysis of Push-out Specimens of Bamboo Scrimber-concrete Composite Structural Connectors

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Abstract: As a kind of hot-pressed bamboo high-strength green biomass engineering material, the research and use of bamboo scrimber is in line with the mainstream development of civil engineering field. In order to investigate the damage pattern and force performance of bamboo scrimber-concrete composite structure and find the suitable shear connector type, this paper simulates and analyzes the force situation of the launched specimens of bamboo scrimber-concrete composite structure under three different connection modes of bolt connector, slot-bolt connector and notch-bolt connector with ABAQUS finite element software combined with the experimental situation, so as to determine the reasonable shear connector type; and further clarifies the use of connectors with comparative study of the force parameters of connectors. Comparative study of the force parameters of the connectors further clarifies the use of the connectors. The results show that: the use of notch-bolt type shear connectors is optimal, the damage mode of the bamboo scrimber-concrete composite structure is the crushing damage of concrete at the notch, and the force pattern is obvious during the loading process; the magnitude of notch-bolt connectors on the shear capacity and shear stiffness of the composite structure decreases with the increase of the embedding depth of the screw, and increases with the increase of the length of the notch, the diameter of the bolt, the length of the screw and the number of the bolts.

Keywords: Bamboo Scrimber-concrete Composite Structures; Numerical Analysis; Notch-bolt joints; Push-out tests; Shear capacity; Load-slip Curves.

1. Introduction

The traditional combined structure is generally a steel-concrete combined structure, which makes full use of the properties of steel and concrete, and is widely used in the construction of various bridges. President Xi Jinping's "dual-carbon" policy and Hunan Province's "three-high, four-new" strategy both emphasize the development and innovation of green industrial structures. In order to reduce the construction waste and environmental pollution produced by traditional materials such as steel and concrete in the production process, the research of new green materials should not be delayed. Bamboo scrimber is a variety of processes on the bamboo fiber bundle processing molding and hot pressing of a new biomass engineering materials, its physical and mechanical properties have been studied [1-4], the density of $1.0\text{--}1.1\text{g/cm}^3$ of bamboo scrimber panels, the average static flexural strength of up to 120MPa, the modulus of elasticity of up to 16GPa, the bending strength of the weight ratio of up to 5.47 times Q235 steel. Based on the green recyclability of bamboo and the excellent mechanical properties of bamboo scrimber, the study of bamboo scrimber-concrete composite structure is of practical significance.

Djoubissie et al [5] found that opening slots, implanting reinforcement and inclination of reinforcement can improve the shear strength and stiffness of wood-concrete combination specimens. Chen Liping [6] found that the shear capacity of wood-concrete rollout specimens was proportional to the length and width of the notch and the diameter of the pegs, and the depth of the notch had a negligible effect. Jiang Yuchen et al [7] found that the shear bearing capacity of wood-concrete combination push-out specimens was proportional to the diameter of the screws and the length and slenderness ratio of the embedded portion, but the concrete strength and the arrangement of the screws did not have a significant effect on it. Shan Bo et al [8-9] found that in glued

bamboo-concrete composite structures, the use of notches can improve the overall slip resistance and ductility, and the increase in screw diameter can improve the shear performance, and proposed 18 mm as the optimum diameter, while the screw strength has almost no effect. Wei Yang et al [10-11] found that notch-pin-peg type shear connectors have excellent mechanical properties in bamboo-concrete composite structures, with better ductility and slip resistance. Bedon et al [12] found that the finite element model can better reflect the shear and compression damage of concrete in the notches of wood-concrete composite beams and the bond properties between different materials, and the analytical results match the experimental values. Wei Chenyu et al [13] found that the shear capacity of screws is proportional to their diameter, tensile strength and embedment depth through ABAQUS finite element simulation, and the arrangement of screws and the strength of concrete do not have much effect on it. At present, there are fewer studies on bamboo scrimber-concrete composite structures, in which the good or bad influence of the shear-resistant connectors on factors such as load carrying capacity and stiffness determines the overall mechanical properties of the composite structure.

This paper establishes the finite element model of recombined bamboo-concrete specimen under three different connection methods through ABAQUS finite element software, and determines the use of notch-bolt type shear connectors through comparative analysis and experimental research. Afterwards, the parameters of the connection were analyzed in order to better utilize the mechanical properties of bamboo scrimber and concrete, and to predict the shear load capacity of the combined structure.

2. Overview of the Test

2.1. Specimen Design

In order to investigate the type of connectors applicable to

the bamboo scrimber-concrete composite structure, with reference to the European code Eurocode 4 [14] and the studies of other scholars on the launching specimens of wood-concrete and bamboo-concrete composite structures [6,8-11,15], three types of connectors were designed.

Three types of connectors were designed: bolt connector, slot-bolt connector, and notch-bolt connector, with specific dimensions as shown in Fig. 1 below, in which the dimensions

of the bamboo scrimber were 250mm×250mm×400mm, the dimensions of the concrete were 250mm×100mm×400mm, the dimensions of the notch were 100mm×250mm×50mm, the dimensions of the slot were 100mm×150mm×50mm, and the bolt diameter was 100mm×150mm×50mm. 150mm×50mm, bolt diameter 18mm, length 180mm. three groups of specimens were numbered as T-W, T-C, T-A respectively.

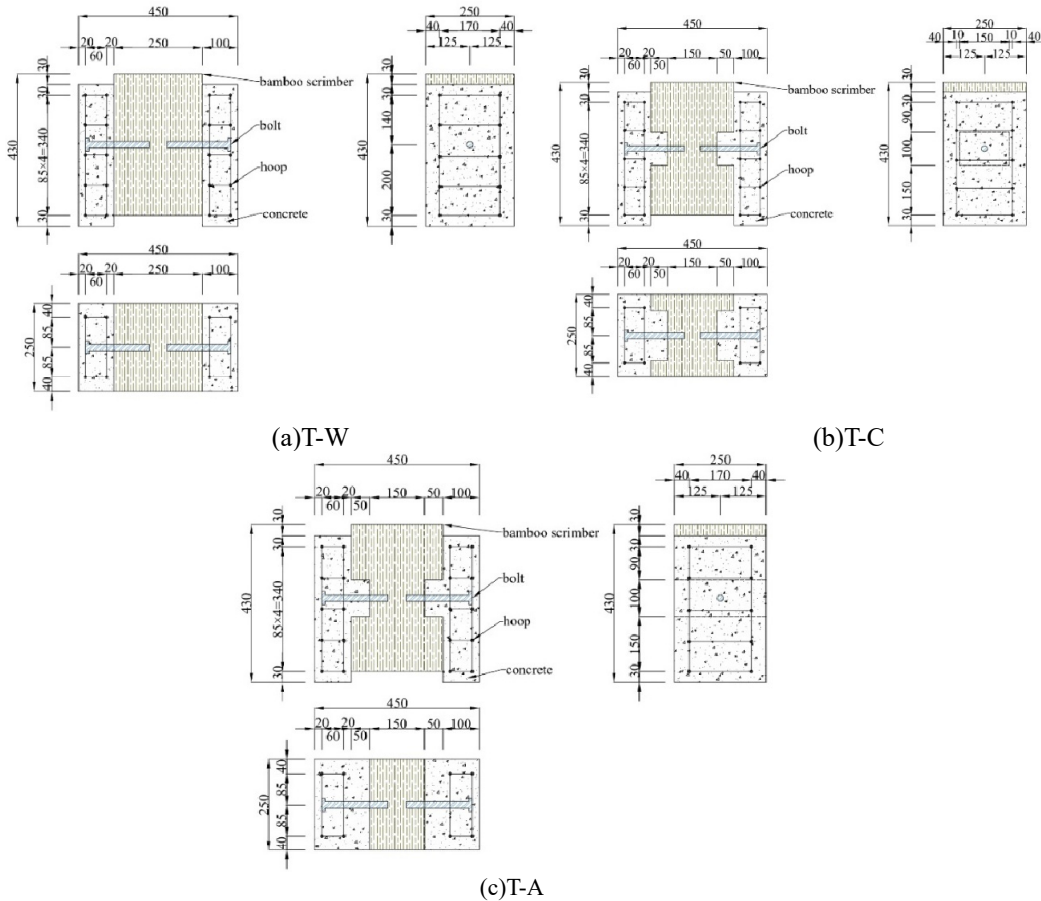


Fig 1. Details of push-out test specimens

2.2. Material Properties

Bamboo scrimber material purchased from Hunan Taohuajiang Bamboo Technology Co., Ltd, with reference to GB/T 1928-2009 “test methods for physical and mechanical properties of wood” [14] measured the bamboo scrimber material of the basic mechanical properties of the numerical

value of the calculation results of the average value is shown in Table 1. the concrete material for the C30 strength. Steel material properties are shown in Table 2, which uses HRB335 Φ8 threaded construction of hoops, the density of 7.85g/cm³; bolts for the 4.8 level of self-supporting zinc-plated nut and screw combination, Poisson's ratio is 0.3.

Table 1. Mechanical properties of bamboo scrimber

Moisture content [%]	Density [g/cm ³]	Tensile strength [MPa]		Compressive strength [MPa]		Shear strength [MPa]	Bending strength [MPa]
		Circular grain	Horizontal grain	Circular grain	Horizontal grain		
5.22	1.105	121.31	9.50	78.69	47.77	39.17	164.59

Table 2. Mechanical properties of steel

Material	Modulus of elasticity [GPa]	Yield strength [MPa]	Maximum strength [MPa]
Hoop	200	335	540
Bolt	205	340	430

3. Computational Modeling

3.1. Finite Element Modeling

ABAQUS finite element software is used for modeling, in which the bamboo scrimber (right part), concrete (left part) and bolt (middle part) are selected SOLID 3D solid units, and the hoop reinforcement adopts truss units, and the specific model and detailed structure are shown in Fig. 2 below. The model is solved by the Newton-Raphson iterative method and the following simplifications are made for the purpose of enhancing the model convergence and speeding up computation. In order to enhance the convergence of the model and speed up the calculation, the following simplifications are carried out.

(1) The 1/4 model is adopted, and the actual processing error and the defects of the material itself are not considered;

(2) The compression direction of the bamboo material is in the paracord direction, and the rest of the directions, i.e., in the radial and tangential directions, are transversely isotropic;

(3) The bolt rod is modeled by effective diameter d_e without considering the influence of threaded section, and the specific formula is as follows:

$$d_e = d - \frac{13}{24} \sqrt{3} p \quad (1)$$

Where: d_e is the effective diameter of the bolt rod (mm); d is the nominal diameter of the bolt rod (mm); p is the thread pitch (mm);

(4) The thickness of the reinforcement adhesive is not considered.

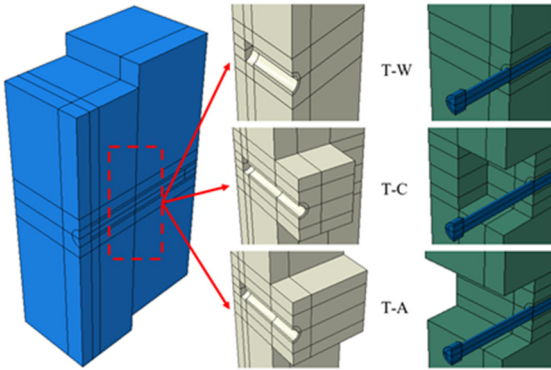


Fig 2. Model detailed construction

3.2. Isomorphic Model

Bamboo scrimber is a typical non-homogeneous anisotropic material, and its intrinsic relationship is complicated. Therefore, the constitutive model of bamboo scrimber is defined as an elastic-plastic model, and the generalized Hooke's law is used to express the stress-strain relationship in the transverse direction during the elastic stage, and the HILL yield criterion is used to express it when it enters into the plastic stage; the constitutive model of concrete is selected as a plastic damage model of concrete; and an ideal elastic-plastic model is used for bolt and reinforcing bars.

3.3. Interact

In order to be able to effectively simulate the interactions between components in ABAQUS, it is possible to define their contact modes independently. The contact mode used in this paper is surface-to-surface contact, and its interaction properties are normal and tangential behavior. In the

tangential direction, we choose to use the Coulomb friction formula to represent the tangential interaction between materials by defining the penalty function, while in the normal direction, we choose to use the hard contact relationship, i.e., only the contact force between surfaces is transmitted.

The main defined interfaces are the interface between the bamboo scrimber and concrete, the interface between the bamboo scrimber and concrete and the bolt rod, the interface between the concrete and the bolt cap, and the remaining interface between the bamboo scrimber and concrete and the bolt (along the compression direction), with friction coefficients of 0.1, 0.4, 0.4, and 0, respectively. The hoop reinforcement in the concrete is embedded in it using built-in constraints, and a reference point is set on the upper surface of the bamboo scrimber section RP1, and the two are coupled and restrained for later applied loads.

3.4. Boundary Conditions and Loading

The constraints are shown in Fig. 3, with concrete on the left side, whose bottom surface is fully constrained; reconstituted bamboo on the right side, whose side constrains the degrees of freedom in the Z direction in the illustration; and the combined surface of the two constrains the degrees of freedom in the X direction in the illustration. The load is applied through point RP1 in the opposite direction to the Y direction in the illustration.

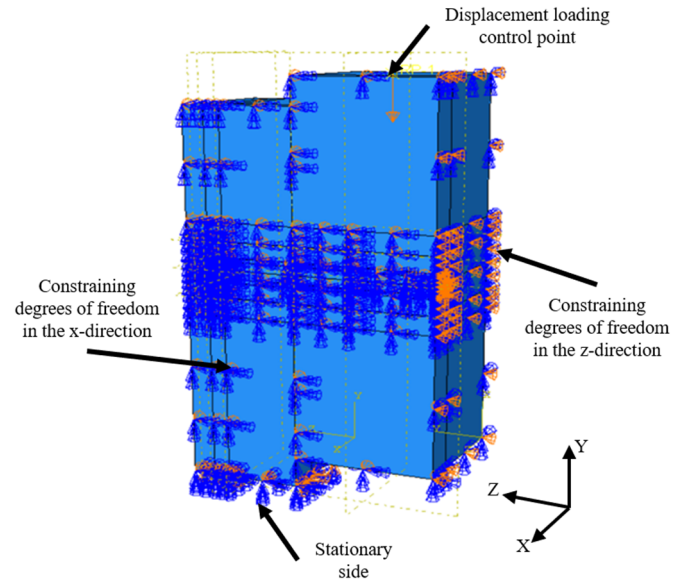


Fig 3. Boundary condition schematic

3.5. Meshing

The bamboo scrimber, concrete, and bolt parts are defined as eight-node linear hexahedral cells with reduced integration, and the hoop part is defined as a truss cell. Through several calculation tests, the global size of the mesh was determined to be 10mm, and at the same time, in order to better analyze the change of the interface, the areas around the bolt rods and bolt holes were finely divided, and the local size was set to be 2mm, and the mesh was divided as shown in Fig. 4, taking T-A as an example.

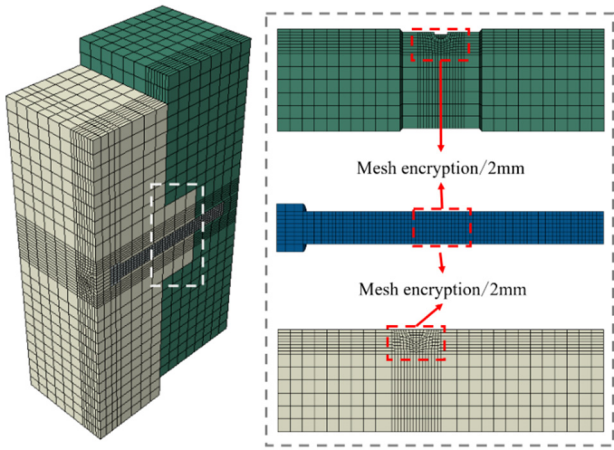


Fig 4. Component meshing of T-A

4. Comparative Analysis of Connectors

4.1. Stress State

The bamboo scrimber, concrete, and bolt parts are defined as eight-node linear hexahedral cells with reduced

4.1.1. Bamboo Scrimber

As shown in Fig. 5, during the launching process of the bamboo scrimber parts of the three groups of components, the stresses mainly expanded along the interface from top to bottom, and the maximum value was generated on both sides near the bolts, and the overall stress distribution was relatively uniform. At the end of loading, the bamboo scrimber of each group did not produce obvious deformation. The stress in the upper part of the groove of the bamboo scrimber of group T-A was larger, and a stress concentration was produced at the top of the hole wall at the junction, with a maximum stress of 66.33 MPa. The stress concentration of bamboo scrimber of group T-C was located in the upper bottom surface of the groove and the bottom surface of the hole wall close to the root, with a maximum stress of 45.05 MPa. The stress concentration in the bamboo scrimber of group T-W was The stress concentration of T-W group bamboo scrimber is at the top of the hole wall at the junction, and the maximum stress value is 260.61MPa.

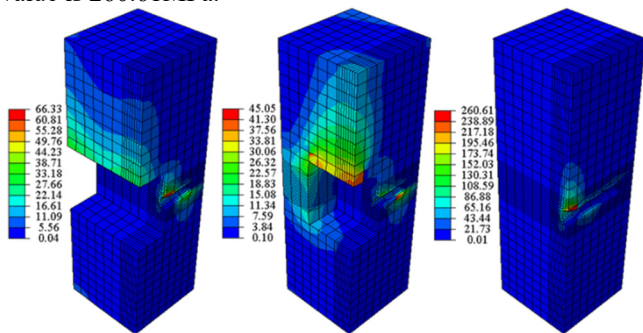


Fig 5. Stress cloud of bamboo scrimber

4.1.2. Concrete

As shown in Fig. 6, the concrete part of the three groups of specimens showed more obvious compression deformation, and the concrete around the hole were obviously damaged by bending in the direction of compression. the stress distribution in the concrete groove and hole in the T-A group was more uniform, with a maximum stress value of 36.73 MPa. the stress concentration of concrete in the T-C group was located in the middle of the hole wall at the top surface, i.e., the junction of the stress, with a maximum stress value of 38.09 MPa. the stress concentration in the T-W group was at

the bottom of the hole wall at the junction and the hole was damaged more seriously, with a maximum stress value of 92.36 MPa. The stress concentration of concrete in group T-W is at the bottom of the hole wall at the junction and the damage of the hole is more serious, and the maximum stress value is 92.36 MPa.

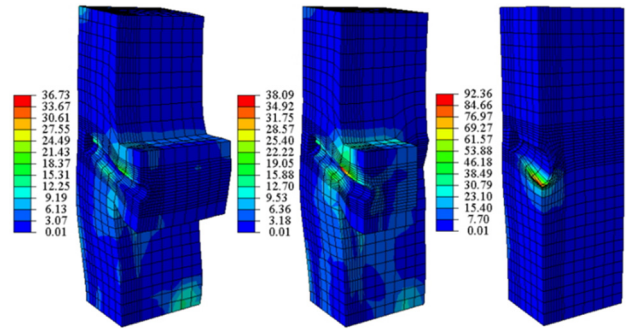


Fig 6. Stress cloud of concrete

4.1.3. Bolt

As shown in Fig. 7, the bolts in the three groups of specimens showed different degrees of bending, in which the bending of the bolts in group T-W was the largest. The stress concentration corresponds to the bamboo scrimber and concrete parts, and the overall stress fluctuation of the bolts in group T-A is the smallest, with the maximum stress value of 388.9 MPa, the maximum stress value of the bolts in group T-C is 404.3 MPa, and the overall stress fluctuation of the bolts in group T-W is the largest and has reached the ultimate damage state.

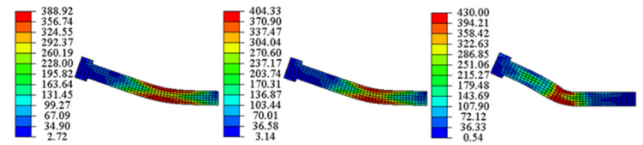


Fig 7. Stress cloud of bolt

4.2. Load-Slip Curve

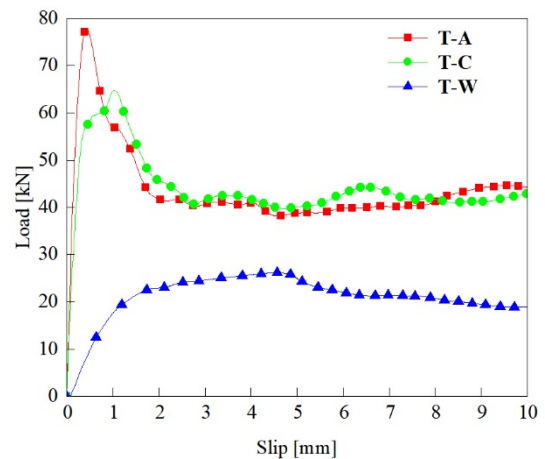


Fig 8. Comparison of load-slip curves

The comparative load-slip curves of the bamboo scrimber-concrete push-out specimens under three different connector connections are shown in Fig. 8. From the figure, it can be seen that in the 1/4 model analysis, the load-slip curve changes of T-A and T-C connections conform to the three stages of elasticity, elastoplasticity, and full plasticity, and the T-W connection has the worst performance. The maximum shear capacity of the T-A group is 77.85 kN, that of the T-C group is 64.72 kN, and that of the T-W group is 26.12 kN. Combined with the analysis of the stress cloud diagrams,

therefore, we choose T-A, which is the notch-bolt type shear connection as the connection of the combined structure in the push-out test. That is, the notch-bolt type shear connection is chosen as the connection method for the combined structure in the push-out test.

5. Test Loading and Testing

5.1. Loading Program and Arrangement

As shown in Fig. 9, According to the finite element simulation, the notch-bolt type shear connectors were selected for the push-out test of the bamboo scrimber-concrete composite structure. An electro-hydraulic servo pressure testing machine was used for loading, with reference to the monotonic static loading regime specified in the British Standard BS EN26891:1991 [16], and the ultimate load capacity in the finite element simulation was selected, and preloading was carried out firstly by loading to $0.4F_{max}$ at a loading rate of $0.2F_{max}/min$ under the force control and maintaining it for 30 seconds, and then unloading was returned to $0.1F_{max}$, also maintained for 30 seconds; into the formal loading stage after the first force control, loading the range of $0.1F_{max} - 0.7F_{max}$, loading rate of $0.2F_{max}/min$; $0.7F_{max}$ after the use of displacement-controlled loading, loading rate of $1mm/min$, loaded to the destruction of the specimen, the descending section of the load reaches $0.8F_{max}$ or slip reaches $15mm$ to stop the loading, and read the corresponding data to record the damage. At the same time, in order to make the push-out specimen uniform pressure, loading in the reorganization of the top of the bamboo first paste a layer of rubber mat, and then on its pad on a steel plate; in the two sides of the bottom of the concrete block laying a layer of fine sand to reduce friction, so that the launch of the specimen of the pressure-bearing surface of the load bearing device in close contact with the loading device.

In the centerline position of the front elevation of the launching specimen, respectively, on both sides of the concrete and bamboo scrimber before and after symmetrically affixed 4, a total of 8 angles, and placed on the test bench to fix the clamping device. After pulling up the electronic displacement meter to an initial value, it was placed vertically and horizontally on the angles by the clamping device, and the relative slip of the combined structure was calculated by the difference of the change of the displacement meters on both sides after loading.

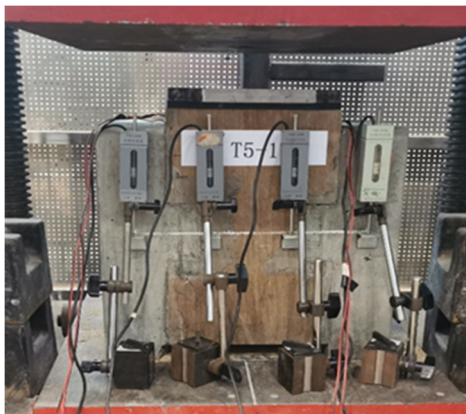


Fig 9. Loading and measurement arrangement diagram

5.2. Destruction Pattern

As shown in Fig. 10, the damage pattern of the specimen was observed after the end of the push-out test, which was

mainly characterized by the shear damage of the grooved concrete tenon at the joint, and there was no obvious crack on the left and right sides of the concrete slab. Chiseling the notch in the concrete to observe the bolt, found embedded in the reorganization of the bolt part of the bamboo and its surrounding are not obvious damage, only near the nut side of the shear has not obvious bending phenomenon.



(a)concrete tenon



(b)bolt

Fig 10. Push-out specimens' damage patterns

5.3. Comparison of Results

As shown in Fig. 11, comparing and analyzing the results of the push-out test and the finite element simulation values, the load-slip curves from the overall trend, are consistent with the three stages of elasticity, elastoplasticity and full plasticity, and the finite element simulation and the test curves are in good agreement. The shear capacity and shear stiffness obtained from both are shown in Table 3, and it can be observed that the shear capacity and initial stiffness values obtained from the finite element simulation of the push-out specimen have an error of 10% in the range of the experimental values, so the finite element simulation is better, and there is a certain degree of reliability.

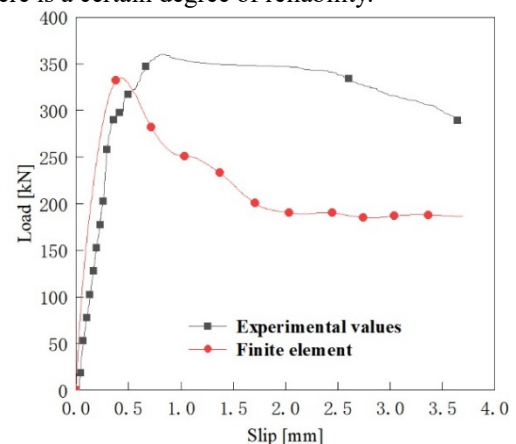


Fig 11. Comparison of load-slip curves

Table 3. Numerical comparison

Shear performance	Experimental values [MPa]	Finite element [MPa]	ratio
Shear capacity	360.23	334.96	0.93
Shear stiffness	831.3	840.26	1.01

6. Parametric Analysis

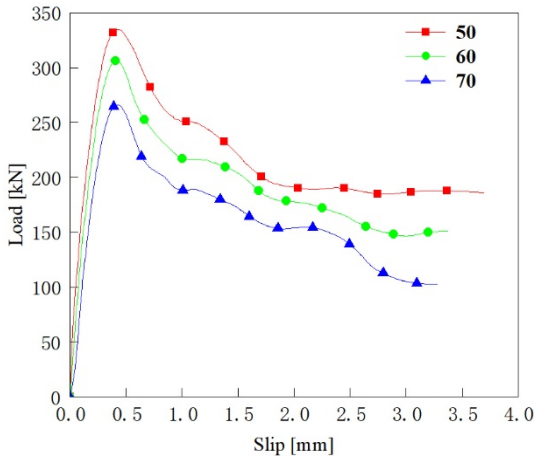
In order to further analyze the effect of notch-bolt connectors on the mechanical properties of the bamboo scrimber-concrete composite structure, the 1/4 finite element model of the push-out specimen was re-established according to the steps in Section 3, using the T-A design dimensions as a blueprint, to study the effect of different parameter changes on the load-slip curve, shear capacity and shear stiffness of the specimen.

Among them, the initial stiffness $K_{0.1}$ was selected for the shear stiffness study, which was taken as the cut line stiffness of the load-slip curve between 10% and 40% of the peak load according to the British Standard BS EN26891 [17] as stated in the following equation:

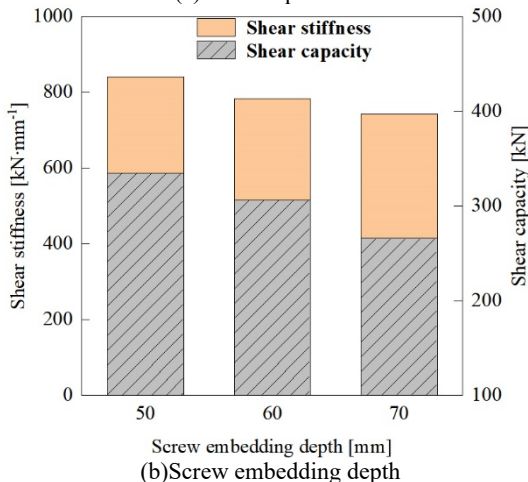
$$K_{0.1} = \frac{0.4F_{\max} - 0.1F_{\max}}{v_{0.4} - v_{0.1}} \quad (2)$$

Where: $K_{0.1}$ is the initial stiffness of the shear connectors; F_{\max} is the ultimate shear bearing capacity (kN); $v_{0.4}$ is the displacement corresponding to 40% peak load (mm); $v_{0.1}$ is the displacement corresponding to 10% peak load (mm).

6.1. Screw Embedding Depth



(a) Load-Slip curve



(b) Screw embedding depth

Fig 12. Effect of different screw embedding depths on specimens

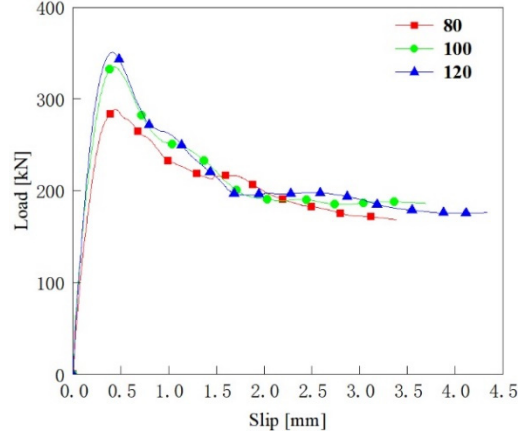
In order to study the effect of bolt embedding depth on the combined structure, the basic parameters were controlled to remain unchanged, and only the size of the depth of the bolt root embedded in the bamboo scrimber was changed to 50 mm, 60 mm and 70 mm, respectively. The specific calculation results are shown in Fig. 12.

From Fig. 12, it can be seen that: (1) The trend of the load-slip curve basically conforms to the three stages of elasticity, elastoplasticity and complete plasticity. With the increase of embedding depth, the peak load value also decreases, and the change amplitude is more obvious. (2) The shear capacity and shear stiffness are negatively correlated with the embedment depth of the screw, in which the shear capacity decreases by 8.6% and 20.5%, respectively, and the shear stiffness decreases by 6.8% and 11.5%, respectively, compared with the 50 mm depth.

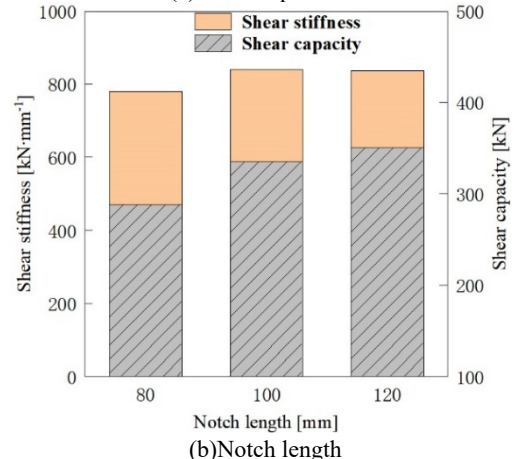
In comparison, the screw embedment depth of 50 mm is more suitable for bamboo scrimber-concrete composite structures with better overall performance.

6.2. Notch Length

In order to study the effect of the length of the notch on the combined structure, the basic parameters are controlled to remain unchanged, and only the size of the length of the notch at the junction is changed, which is 80 mm, 100 mm and 120 mm, respectively. The specific calculation results are shown in Fig. 13.



(a) Load-Slip curve



(b) Notch length

Fig 13. Effect of different notch lengths on specimens

From Fig. 13, it can be seen that: (1) The trend of the load-slip curve basically conforms to the three stages of elasticity, elastoplasticity and complete plasticity. With the increase of notch length, the peak load value also increases, and the change amplitude is relatively obvious. (2) The shear capacity and shear stiffness are positively correlated with the notch length, in which the shear capacity decreases by 13.9% and increases by 4.6%, and the shear stiffness decreases by 7.1% and 0.4%, respectively, compared with the 100 mm length.

In comparison, the notch lengths of 100mm and 120mm have little effect on the overall structural performance. The notch length of 100 mm can be selected for bamboo scrimber-concrete composite structures.

6.3. Bolt Diameter

In order to study the effect of bolt diameter on the combined structure, the basic parameters are controlled to remain unchanged, and only the size of the bolt diameter is changed, which is 16mm, 18mm and 20mm, respectively. The specific calculation results are shown in Fig. 14.

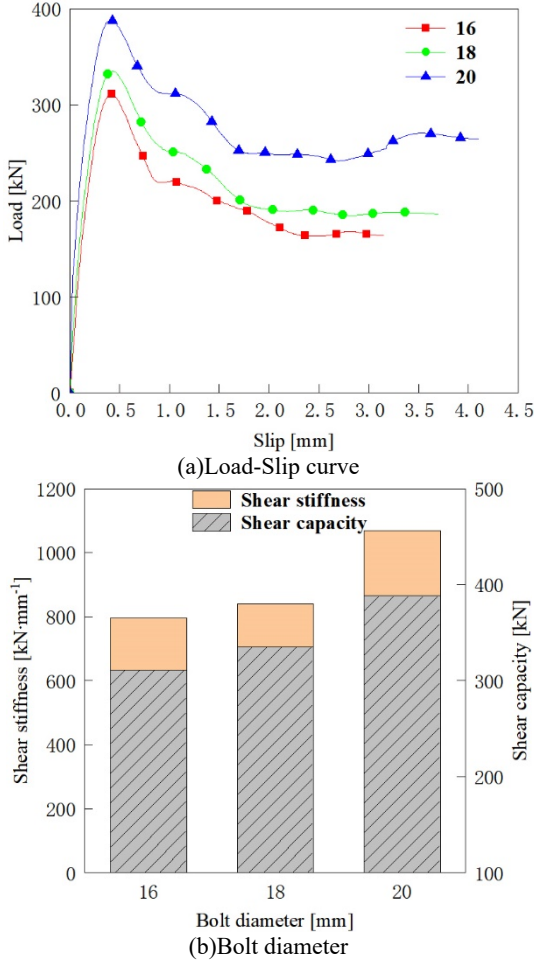


Fig 14. Effect of different bolt diameters on specimens

From Fig. 14, it can be seen that: (1) The trend of the load-slip curve basically conforms to the three stages of elasticity, elastoplasticity and complete plasticity. With the increase of bolt diameter, the peak load value also increases, and the change amplitude is more obvious. (2) The shear capacity and shear stiffness were positively correlated with the bolt diameter, in which the shear capacity decreased by 7.1% and increased by 15.9%, and the shear stiffness decreased by 5.4% and increased by 27%, respectively, compared with the 18 mm diameter.

In comparison, the size of the bolt diameter in the bamboo

scrimber-concrete composite structure should be selected according to the actual use and economic conditions.

6.4. Thread Length

In order to study the effect of thread length on the combined structure, the basic parameters are controlled to remain unchanged, and only the size of the thread length is changed, which is 160mm, 170mm and 180mm, respectively. The specific calculation results are shown in Fig. 15.

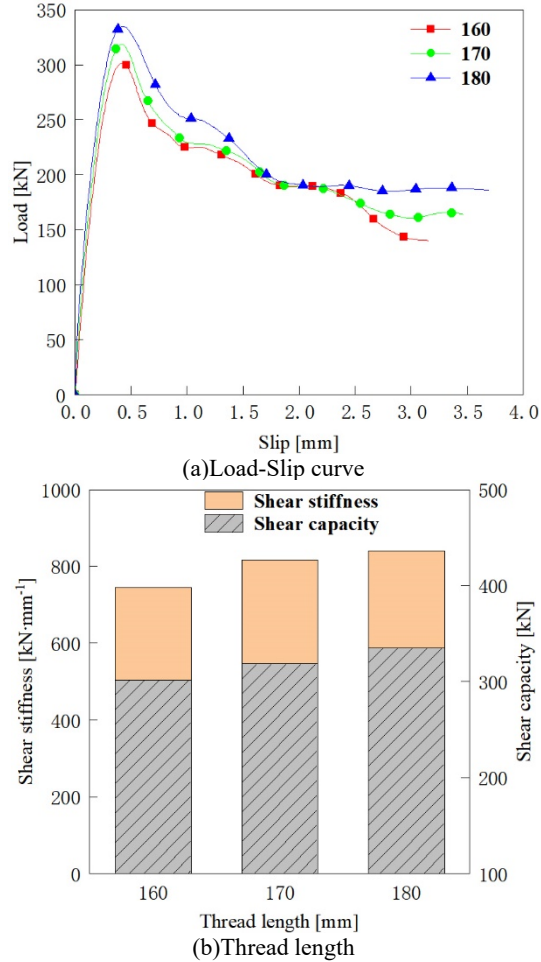


Fig 15. Effect of different thread lengths on specimens

From Fig. 15, it can be seen that: (1) The trend of the load-slip curve basically conforms to the three stages of elasticity, elastoplasticity and complete plasticity. With the increase of thread length, the peak load value also increases, and the change amplitude is small. (2) The shear capacity and shear stiffness were positively correlated with the thread length, in which the shear capacity decreased by 10% and 4.9%, respectively, and the shear stiffness decreased by 11.4% and 2.7%, respectively, from the length of 180 mm to the length of 100 mm.

In comparison, since the thread length has little effect on the overall performance of the combined structure, the 180 mm thread length with the largest value can be considered for selection.

6.5. Number of Bolt

In order to study the effect of the number of bolts on the combined structure, the basic parameters were controlled to remain unchanged, and only the number of bolts implanted in the bamboo scrimber was changed to 0, 1 and 2, respectively. The specific calculation results are shown in Fig. 16.

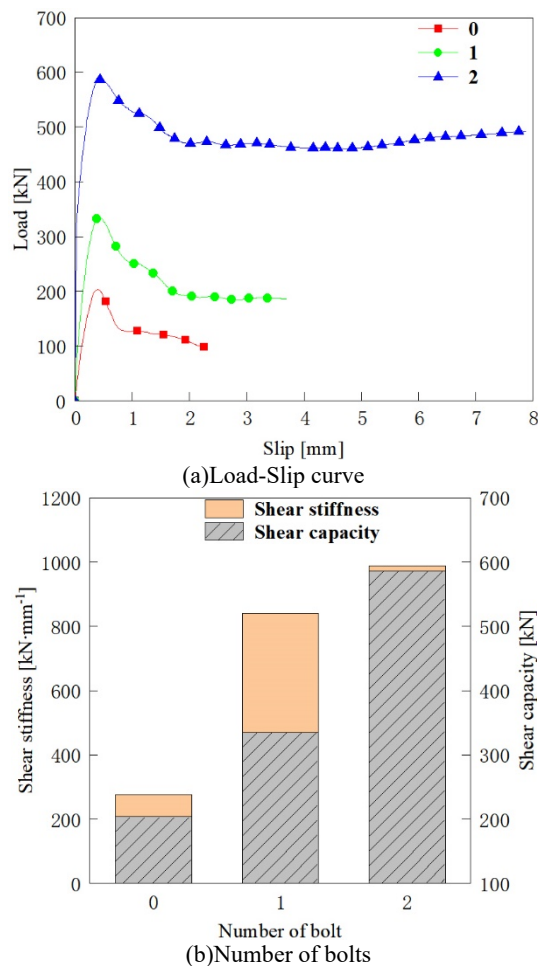


Fig 16. Effect of different number of bolts on specimens

From Fig. 16, it can be seen that: (1) The trend of the load-slip curve basically conforms to the three stages of elasticity, elastoplasticity and complete plasticity. With the increase of the number of bolts, the peak load value also increases significantly, and the change amplitude is the most obvious among the five groups of parameters. (2) The shear capacity and shear stiffness are positively correlated with the number of bolts, in which the shear capacity decreases by 39.2% and increases by 75%, and the shear stiffness decreases by 67.2% and increases by 17.5% compared with that of a single bolt, respectively. And due to the effect of group nailing, the single-nail bearing capacity and stiffness of the double-bolt group decreased by 12.5% and 41.3%, respectively, compared with that of the single-bolt group.

In comparison, the number of bolts in the bamboo scrimber-concrete composite structure should be selected according to the actual design of components and economic conditions.

7. Summary

(1) The bamboo scrimber used in this paper has better basic mechanical properties than the traditional engineering materials, and when it is used in the combined structure, it can better utilize the performance of each material.

(2) The finite element model of bamboo scrimber-concrete notch-bolt push-out specimen under static load established by ABAQUS better reflects the damage and force performance of the combined structure during the actual loading process, which provides a reference for the future simulation of the beam model.

(3) In the bamboo scrimber-concrete composite structure, the notch-bolt connectors are superior to the bolt connectors and slot-bolt connectors. The shear bearing capacity and shear stiffness of the structure are negatively correlated with the embedment depth of the screw and positively correlated with the notch length, bolt diameter, thread length and number of bolts.

(4) According to the finite element parameter analysis of bamboo scrimber-concrete composite structural joints in this paper, for the notch-bolt type shear joints, it is recommended to choose 18mm bolt diameter, 180mm thread length and 100mm notch length, and the embedded depth of the screw is 50mm, and the number of bolts is chosen in combination with the specific components.

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