

Mechanical Model of Directional Continuous Bamboo Fiber Opening

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Mechanical Model of Directional Continuous Bamboo Fiber Opening

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Abstract— Based on the principle of directional continuous fiber opening of bamboo, the calculation model of the continuous beams in opening bamboo fiber is proposed. The continuous beam method is used to derive the moment equation of bamboo continuous fiber opening process. The mechanical model of bamboo directional continuous fiber opening is established, with the quantitative relationship found between the fiber opening parameters, e.g. the external load, the roll distance, the strength of the bamboo. The fiber opening test further verifies that the bamboo fiber opening model is correct. The research in this paper provides a theoretical basis for the precise control of directional continuous fiber opening of bamboo.

Index Terms— bamboo fiber; directional fiber opening; mechanical model; continuous beam; bamboo

I. INTRODUCTION

Bamboo fiber is a natural fiber extracted from bamboo through mechanical and physical methods. Due to the wide distribution of bamboo, the renewable nature and the superior performance of bamboo fiber, the research on natural bamboo fiber and its composite materials has been increasing in recent years. The bamboo fiber has already been applied in the applications such as mattress and car interior [1]. Regarding bamboo fiber research, it mainly focuses on the structure and performance of the bamboo fiber, post-treatment, and fiber composites [2][3]. The mechanical fiber opening is the key process of bamboo fiber extraction, and it has always been a weak link in bamboo fiber research. The study for bamboo directional fiber opening isn't found in the existing research.

The directional continuous opening of bamboo is performing the multi-roll continuous loading on bamboo trips to realize the directional grain opening of bamboo fiber. Due to its high efficiency and resulted neat fiber length, it is the main method for producing bamboo fiber similar to hemp fibers. The theoretical study of bamboo fiber opening with mechanical method lags behind, causing the current directional bamboo fiber opening is still in the initial stage of simple and empirical mechanical process. There can be fiber breakage or insufficient debonding in the current process, even the phenomenon of fiber winding, which seriously affects the post-treatment process of bamboo fiber. Consequently, the quality of bamboo fiber is difficult to guarantee. Finding the principles of continuous loading and fiber opening of bamboo with the suitable parameters identified is the only way to fundamentally improve the processing quality of bamboo fiber, which is also an urgent problem to be solved.

Therefore, by analyzing the ideal load distribution of bamboo continuous fiber opening, it is proposed to use continuous beam and its two equivalent virtual beams to express its stress state. Using the principle of continuous beam to solve the mechanical

model of continuous fiber opening, the law of debonding and separating fibers from bamboo is revealed, which provides a theoretical basis for the controllable processing of directional bamboo fiber opening [4].

II. THE THEORETICAL MODEL OF DIRECTIONAL FIBER OPENING OF BAMBOO

A. Principle of directional fiber opening of bamboo

The vascular bundles in the bamboo are distributed in the matrix structure in a certain manner, and the thick-walled cells in the vascular bundle account for about 40% and are connected into the fiber bundle. The remaining thin-walled cells of the bamboo are generally regarded as the matrix surrounding the fiber bundle. As shown in Fig. 1, the density of radial vascular bundles increases from the yellow layer to the green layer, the single-layer vascular bundles are evenly distributed along the radial direction with the structure volume mostly the same [5] [6]. Therefore, bamboo can be regarded as a natural two-phase fiber reinforced composite material, which has the characteristics of laminated structure in the radial [7-9]. In essence, it is a type of non-uniform fiber reinforced gradient composite material.

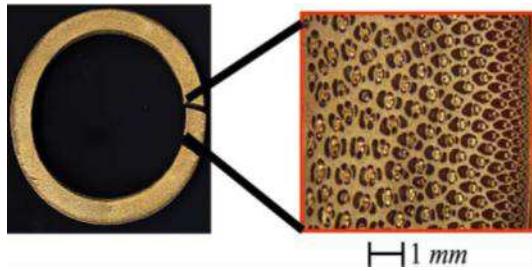


Fig. 1. Cross section of culm showing radial distribution of fibers

Bamboo softened, its plasticity is greatly improved, and the modulus of the fibers is much larger than that of the matrix material [10], and the fibers are arranged in parallel along the longitudinal direction, which makes it possible for bamboo to open fibers continuously under directional loading. As shown in Fig. 2, under the continuous action of multiple rollers, the matrix structure of bamboo strip is destroyed so that the fibers of bamboo strips are opened along parallel to grain from the laminated structure.

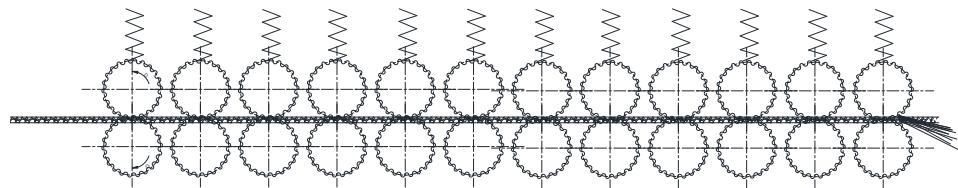


Fig. 2. Schematic diagram of directional fiber opening of bamboo

When the bamboo is under directional fiber opening with the effect of multiple pairs of rollers, the bamboo strip is equivalent to the continuous beam, with its cross-section affected by bending moments and shear internal forces. When the bamboo strip is loaded, the bending deformation and the parallel-to-grain tensile stress are generated by the upper and lower rollers. Then the bamboo substrate is broken and the fiber is debonded and separated as a result of the repeated rolling of the roller. Therefore, it is considered that the continuous fiber opening of the bamboo is a result of the parallel-to-grain bending deformation. It is clear that the conditions of raw bamboo, the load mode and the load strength etc. are the main factors affecting the fiber opening effect.

B. Calculation model of bamboo directional fiber opening

As shown in Fig. 2, the status of the directional fiber opening can be considered as the continuous beam in structural engineering, which applies symmetry circulating stress on the bamboo strip. The bamboo strip is continuously loaded and opened under the action of many pairs of rollers. In the continuous fiber opening, each pair of rollers is regarded as the fiber-opening force roller and the supporting roller, and the adjacent rollers are reversely loaded, as shown in Fig. 3(a). When bamboo strips are cracked, the reverse load is applied in sequence, and the tensile and compressive cyclic stress is generated on the bamboo strips, so that the upper and lower sides of the bamboo are subjected to tensile and compressive stresses in sequence, which is beneficial to matrix destruction and fiber separation[11][12].

In order to solve the continuous beam of Fig. 3(a), the force state can be replaced by two equivalent virtual beams. By separately solving and superimposing, the fiber opening moment acting on the bamboo strip is obtained, and subsequently the fiber opening stress is derived. According to the loading state of the bamboo strip in fiber opening (see Fig. 3(a)), the virtual beam successively takes support and loads to the arrangement of the rollers. As shown in Fig. 3(b), (c), the support and the load are misaligned and the load acts in the opposite direction.

Based on the superposition principle, the bending moment of any cross-section on the beam in Fig. 3(a) should be the sum of the corresponding bending moments of the two virtual beams, i.e.

$$M_\beta = M_{\beta 1} + M_{\beta 2} \quad (1)$$

Where M_β , $M_{\beta 1}$ and $M_{\beta 2}$ are the bending moments on the bamboo beam and the virtual beams 1, 2 respectively. Therefore, the virtual beams can synthesize the equivalent to the state in the directional fiber opening shown in Fig. 3(a).

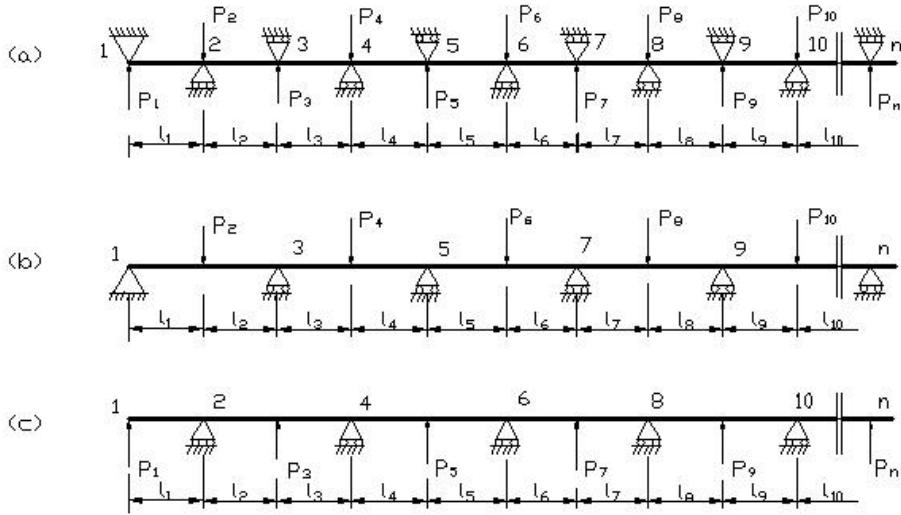


Fig. 3. Schematic of bamboo rolling opening and its virtual beam calculation

III. MECHANICAL MODEL OF BAMBOO DIRECTIONAL FIBER OPENING

A. Moment equation of virtual continuous beam

The continuous beam solving method is applied to the above virtual beam which is simplified into a simple supported beam. Then the bending moment and the shear force distribution on the beam can be derived.

According to the theory of composite material mechanics, the parallel-to-grain tensile strength of bamboo depends on the strength of the fiber. For the convenience of the virtual beam solution, the paper puts forward three assumes: 1)The mechanical properties of each layer of bamboo are the same;2) The elastic modulus of bamboo along parallel to the grain remains unchanged when bamboo fiber opening; 3) The cross section of bamboo beam remains unchanged with bending deformation.

The solve of the virtual beam 1 is shown in Fig. 4. The intermediate supports of the continuous virtual beam in Fig. 3(b) are all replaced by a hinge with couples of forces X_3, X_5, X_7 , etc. (Fig. 4(a)). These couples of forces are the fulcrum bending moments. For any intermediate hinge, the left section should have the same angle of rotation on the right section, with the relative rotation angle at zero. The deflection curve of the adjacent two simply supported beams maintains the continuity of the corner at the fulcrum, which is consistent with the original continuous beam (Fig. 3 (b)).

The support 5 is selected to study the relative rotation angles of the simple support beams 35, 57 at the support 5. As shown in Fig. 4, beam 35 bears load P_4 and the fulcrum bending moments X_3, X_5 ; beam 57 bears load P_6 and fulcrum bending moments X_5, X_7 .

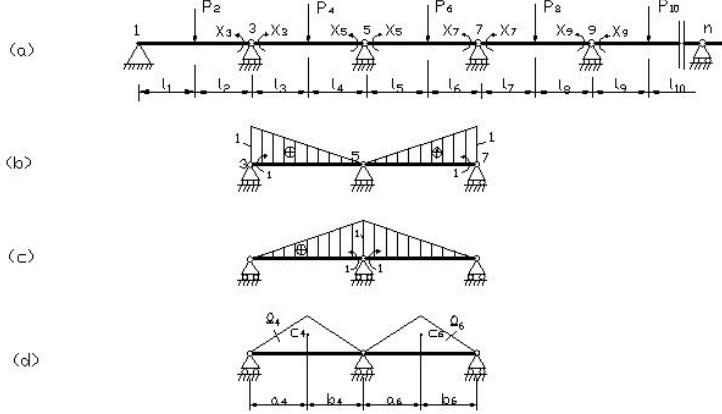


Fig. 4. virtual beam 1 solution

The relative rotation angle is indicated by the following symbol:

- The relative rotation angle of the load P₄, P₆ at the fulcrum 5: δ_{5p}
- The relative rotation angle of X₃ at the fulcrum 5: $\delta_{5X_3} = \delta_{53}X_3$
- The relative rotation angle of X₅ at the fulcrum 5: $\delta_{5X_5} = \delta_{55}X_5$
- The relative rotation angle of X₇ at the fulcrum 5: $\delta_{5X_7} = \delta_{57}X_7$

Therefore, the zero relative rotation angle of the fulcrum 5 can be expressed as

$$\delta_{53}X_3 + \delta_{55}X_5 + \delta_{57}X_7 + \delta_{5p} = 0 \quad (2)$$

The moment diagram with unity X₃/X₅/X₇ is drawn in Fig. 4(b), (c)). The load moment diagram is drawn in (Fig. 4(d)), with Ω_4 and Ω_6 as the areas of the bending moment diagrams of the simple supported beams of 35 and 57. The distance between the left and right fulcrums of their centroids is marked (a4, b6 in Fig. 4(d)).

The graphic multiplication method yields

$$\begin{aligned} \delta_{35} &= \frac{1}{EJ_4} \times \frac{l_3 + l_4}{2} \times \frac{1}{3} = \frac{l_3 + l_4}{6EJ_4} \\ \delta_{55} &= \frac{1}{EJ_4} \times \frac{l_3 + l_4}{2} \times \frac{2}{3} + \frac{1}{EJ_6} \times \frac{l_5 + l_6}{2} \times \frac{2}{3} = \frac{l_3 + l_4}{3EJ_4} + \frac{l_5 + l_6}{3EJ_6} \\ \delta_{57} &= \frac{1}{EJ_6} \times \frac{l_5 + l_6}{2} \times \frac{1}{3} = \frac{l_5 + l_6}{6EJ_6} \\ \delta_{5p} &= \frac{1}{EJ_4} \times \Omega_4 \times \frac{a_4}{l_3 + l_4} + \frac{1}{EJ_6} \times \Omega_6 \times \frac{b_6}{l_5 + l_6} \end{aligned}$$

By substituting into (2), E is canceled with X₃, X₅, X₇ replaced with M'₃, M'₅, M'₇, which yields

$$M'_3 \frac{l_3 + l_4}{J_4} + 2M'_5 \left(\frac{l_3 + l_4}{J_4} + \frac{l_5 + l_6}{J_6} \right) + M'_7 \frac{l_5 + l_6}{J_6} + 6 \left(\frac{\Omega_4 a_4}{(l_3 + l_4) J_4} + \frac{\Omega_6 b_6}{(l_5 + l_6) J_6} \right) = 0 \quad (3)$$

According to assume 3), the cross section of bamboo beam remains unchanged, i.e. $J_4=J_6$. The above formula becomes

$$M'_3(l_3 + l_4) + 2M'_5(l_3 + l_4 + l_5 + l_6) + M'_7(l_5 + l_6) + 6 \left(\frac{\Omega_4 a_4}{(l_3 + l_4)} + \frac{\Omega_6 b_6}{(l_5 + l_6)} \right) = 0 \quad (4)$$

The above formula is the bending moment equation of the virtual beam in bamboo fiber opening. It can also be applied to other intermediate hinges. Considering the existing fiber-opening equipment, for the simplicity of solving, the following calculation stands for any intermediate hinge i

Assuming

$$l_i = l_{i+1} = l, P_i = P_{i+1} = P$$

Then

$$M'_3 = M'_5 = M'_7 = \dots = M$$

For fulcrum 5, as shown in Fig. 4(d)

$$a_4 = b_6 = l, \Omega_4 = \Omega_6 = \frac{P}{2}l^2$$

Substituting into (4), it yields

$$M = -\frac{1}{4}Pl \quad (5)$$

The bending moments of each pair of rollers are

$$M'_3 = M'_5 = M'_7 = \dots = -\frac{1}{4}Pl \quad (6)$$

Similarly, for virtual beam 2, Figure 3(b) yields

$$M'_4 = M'_6 = M'_8 = \dots = \frac{1}{4}Pl \quad (7)$$

B. Moment and shear on continuous beams

As shown in Fig. 5, the two continuous virtual beams are individually disassembled into three simple support beams subjected to the bending moment of the fulcrum (same process for all simple support beams). The reaction force of each fulcrum Y and the load of the rollers P can be derived. The bending moment diagram of each simple support beam is connected to yield the bending moment diagram of the virtual beam.

For the beams 35 and 57 in Fig. 5(a) and the beams 24 and 46 in Fig. 5 (d), the following equations stand

$$P_4 = P_6 = Y_3 = Y_5 = P, P_3 = P_5 = P_7 = Y_2 = Y_4 = Y_6 = P$$

For the 13 beams in Fig. 5(a), the solution is

$$Y_1 = \frac{1}{4}P, P_2 = \frac{3}{4}P \quad (8)$$

For the 14 beams in Fig. 5(d), the solution is

$$P_1 = \frac{1}{4}P, Y_2 = P_2 = \frac{3}{4}P \quad (9)$$

The bending moment diagrams of the two virtual beams are individually drawn, as shown in Fig. 5(c) and (f). The bending moment values of the two virtual beams are superposed following formula (1), and the combined bending moment diagram is shown in Fig. 5(g). The maximum fiber opening bending moment is at each roller with the value of

$$M_2 = M_3 = M_4 = \dots = \pm \frac{1}{2}Pl \quad (10)$$

The shear force diagram is shown in Fig. 5(h), and the maximum shear force is at each roller with the value of

$$Q_3 = Q_4 = \dots = 2P \quad (11)$$

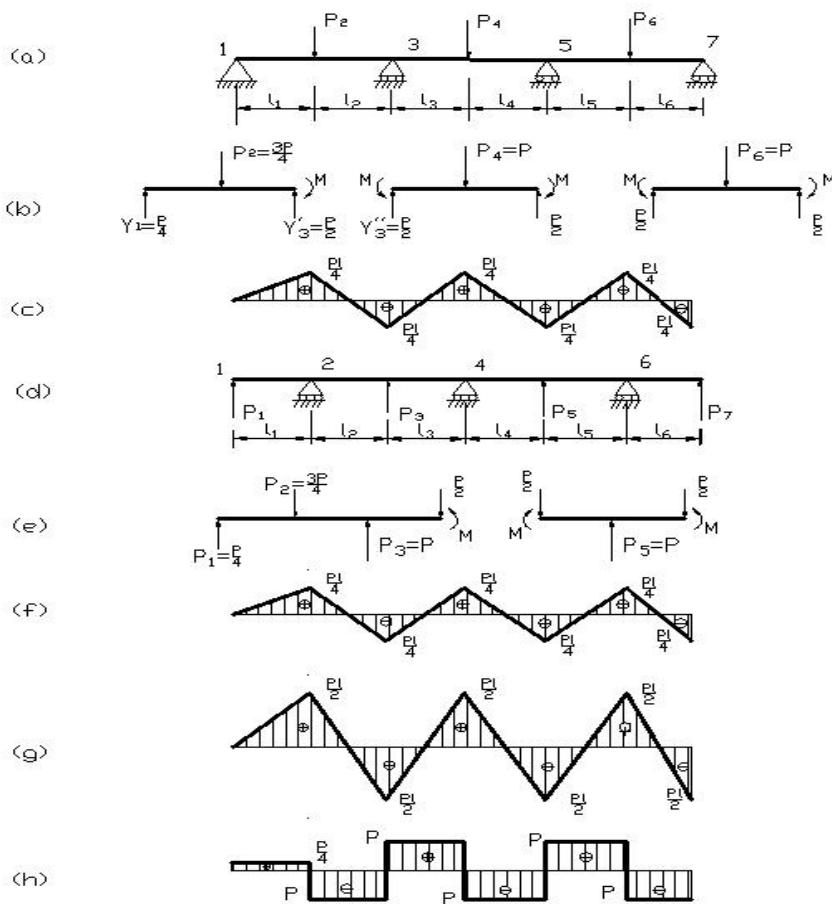


Fig. 5. Bamboo strip continuous beam solution

C. The bending stress of bamboo

1) Bending normal stress

Following the above analysis, in the process of bamboo fiber opening, the moment of bamboo beam changes as illustrated in Fig. 5(g). And the bending moment reaches the maximum at each roller with the direction changes sequentially. Based on theory of material mechanics, when the bamboo is being loaded, the bending stress of any layer in cross section at each pair of rollers is

$$\sigma_i = \frac{M_i \cdot y}{J}$$

Where, y : the distance from any layer of bamboo to the neutral layer (intermediate layer),

J : the section of bamboo strip is considered as rectangle, moment of inertia $J = \frac{bh^3}{12}$,

(b: width of bamboo strip, h: thickness of bamboo strip)

Following assume 1, the neutral layer of bamboo is intermediate layer along the thickness(h) direction in cross section of bamboo strip, the stress in the upper/bottom layer of bamboo is considered equal. The maximum stress is on the outermost layer (green, yellow layer) of the bamboo. Combined with the formula (10), the maximum bending stress at each roller is

$$\sigma_{\max} = \frac{3Pl}{bh^2} \quad (12)$$

2) Shear stress

The maximum shear stress is also at rollers. From the material mechanics, the shear stress of any layer in the cross section of the bamboo beam at rollers with a distance from the neutral layer y is

$$\tau_i = \frac{3Q_i}{2bh} \left(1 - \frac{4y^2}{h^2}\right)$$

Combine formula (11), the maximum shear stress occurs in the neutral layer at rollers with the value as

$$\tau_{\max} = \frac{3P}{bh} \quad (13)$$

It can be seen from (12) and (13) that $\sigma_{\max} \gg \tau_{\max}$ ($\frac{\sigma_{\max}}{\tau_{\max}} = \frac{l}{h}$). It is indicated that the layers of bamboo are mainly opened under the action of bending normal stress.

D. Mechanical model of bamboo fiber opening

Bamboo fiber opening is to crack the matrix in bamboo and keep the fiber intact. The stress of the outermost layer is the largest for each section of bamboo strip, while it is the smallest in the neutral layer. Therefore, the opening bamboo fiber should meet to that the fiber in outer layer of bamboo isn't break, and the matrix in neutral layer is creaked.

1) Opening the outermost layer in bamboo

Following to the previous analysis, the bamboo material is mainly opened under the bending normal(tensile or compressive) stress, regardless of other stresses, in a uniaxial stress state.

The research shows that when the applied longitudinal compressive stress on bamboo reaches the compressive limit , the fiber and bamboo are buckled without fiber breakage [13][14]. And bending tensile deformation is more effective than compression deformation for the matrix cracking in bamboo [11]. Therefore,it is considered as stretching. The analysis of a softened bamboo material shows that the matrix begins to crack when the tensile yield limit is reaches, following which the increase with stress until the fracture limit. Finally, the fiber is break [15].

Therefore, the fiber opening stress of the outermost layer in bamboo should be satisfied.

$$\sigma_s < \sigma_{max} < \sigma_b \quad (14)$$

Where σ_s is the yield strength ; σ_b is the fracture strength of bamboo.

Combined with the formula (12), the load P_i is:

$$\frac{bh^2}{3l}\sigma_s < P_i < \frac{bh^2}{3l}\sigma_b \quad i:3-n \quad (15)$$

2) Opening the neutral layer in bamboo

In order to crack the neutral layer of bamboo, the cross section of the bamboo beam at rollers should be sequentially yields from outermost layer to neutral layer under bending load. According to the theory in elastic-plastic mechanics, the weak and enhanced features of softened bamboo during tensile deformation can be ignored[15], and softened bamboo is as an ideal elastoplastic material.The bending moment of the section of bamboo beam begins to yield and the complete yields are termed as M_s and M_F , respectively:

$$M_s = \frac{bh^2}{6}\sigma_s, \quad M_F = \frac{bh^2}{4}\sigma_s$$

The bending moment at each roller should be satisfied,

$$M_i > M_F \quad (16)$$

Combined with the formula (10), the load P_i is

$$P_i > \frac{bh^2}{2l}\sigma_s \quad i=3 \sim n \quad (17)$$

According to the formula (15) and (17),(,)The exerting load on the bamboo beam with the outermost layer at section cracking and the neutral layer cracking, and which of fiber begins to break are termed as P_s , P_F and P_b , respectively:

$$P_s = \frac{bh^2}{3l}\sigma_s, P_F = \frac{bh^2}{2l}\sigma_s, P_b = \frac{bh^2}{3l}\sigma_b \quad (18)$$

Combined with the formula(9), the mechanical model of fiber opening of bamboo is:

$$\frac{bh^2}{2l}\sigma_s < P_i < \frac{bh^2}{3l}\sigma_b, \quad P_i = P_{i+1}, \quad i:3-n \quad (19)$$

$$P_1 = \frac{1}{4}P_3 \quad P_2 = \frac{3}{4}P_3$$

Where n is number of the pairs of rollers; $l=D+\Delta$, D is diameter of the rollers, Δ is the gap between adjacent pairs of rollers.

Generally $D \gg \Delta$, and the formula (19) can be expressed as

$$\frac{bh^2}{2D}\sigma_s < P_i < \frac{bh^2}{3D}\sigma_b, \quad P_i = P_{i+1}, \quad i:3-n \quad (20)$$

$$P_1 = \frac{1}{4}P_3 \quad P_2 = \frac{3}{4}P_3$$

IV. EXPERIMENTAL VERIFICATION AND ANALYSIS

The 4-year-old moso bamboo strips from Zhejiang Lin'an are prepared as the experimental specimens. The specimens are cut to 1.8m long from middle part of bamboo and evenly split into a total of 2 groups, with the width b of 30mm and the thickness h of 15mm. After softening, the yield tensile strength and fracture strength of moso bamboo under extend parallel to the grain are 36 MPa and 68MPa respectively. The diameter of the rollers of test prototype is 175mm, the gap between adjacent pairs of rollers is 5mm.

According to the formula (18) , (19), the corresponding load values can be calculated, which are listed in Table 1.

TABLE 1 THEORETICAL AND EXPERIMENTAL PARAMETERS FOR THE LOAD OF EACH PAIR OF ROLLERS

Calculation parameters Load	h(mm)	b(mm)	l (mm)	σ_s (MPa)	σ_b (MPa)
	15	30	180	36	68
$P_i(i=3\sim 9)$	P_s (kg)		P_F (kg)		P_b (kg)
Model valves	45		67.5		85
Experimental parameters	I group ($P_i:P_s \sim P_F$) (kg)			II group ($P_i:P_F \sim P_b$) (kg)	
	P_i 56	P_1 14	P_2 42	P_i 76	P_1 19
					P_2 57

The two groups of bamboo strips are loaded according to I group and II group in Table 1. Next, the cross-section opening of the bamboo strips are observed, which is shown in Fig. 6. After processing , (a)and(b) shows the end face of the strips sequentially.



Fig. 6. End face of bamboo specimen in bamboo opening test

It can clearly be seen that the outer layers in bamboo were opened, and middle layers weren't opened in Fig. 6(a), while every layer in bamboo were opened in Fig. 6(b). The experimental results were consistent with the above analysis. After the experiment, It can be seen from II group and Fig. 6(b) that the fibers in each layer were completely separated without any fiber breakage. The experiments proves that the calculated load parameters from the proposed model are appropriate.

V. CONCLUSION

- 1) A calculation model for directional continuous bamboo fiber opening is proposed by using virtual continuous beam. By applying the engineering continuous beam solving method, the bending stress distribution in the process of directional opening bamboo fiber is obtained by establishing the moment equation in bamboo beam. This paper provides a new method for the study of bamboo directional fiber opening.
- 2) The mechanical model of continuous bamboo fiber opening is established, with the loading conditions obtained. The quantitative relationship between the opening load, the opening parameters of the roller and bamboo parameters is obtained. The experiments proves that the calculated load parameters from the proposed model are appropriate.
- 3) The load acting on the bamboo beam with the outermost layer at section cracking and the neutral layer cracking, and which of fiber begins to break are obtained, the research provides a theoretical basis for the precise control of directional continuous fiber opening of bamboo.

Declarations

Availability of data and materials

Not applicable

Competing interests

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

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Authors' contributions

Wei Zhang: Methodology, Writing - Original Draf, Writing - Review & Editing

Wenbin Yao: Conceptualization, Validation

Weipeng Yu: Materials, Performed the experiments

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Figures

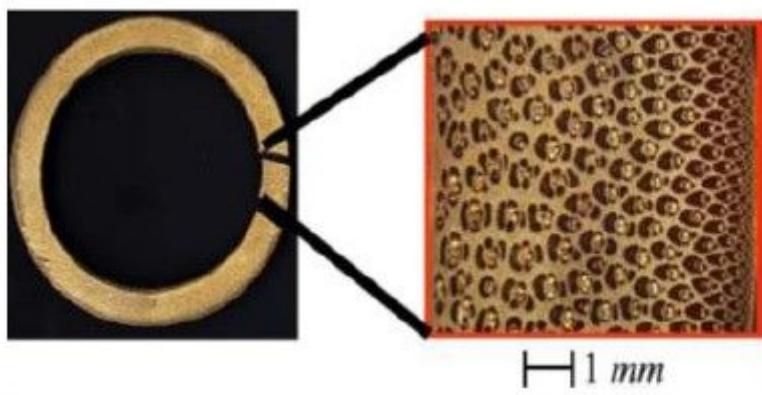


Figure 1

Cross section of culm showing radial distribution of fibers

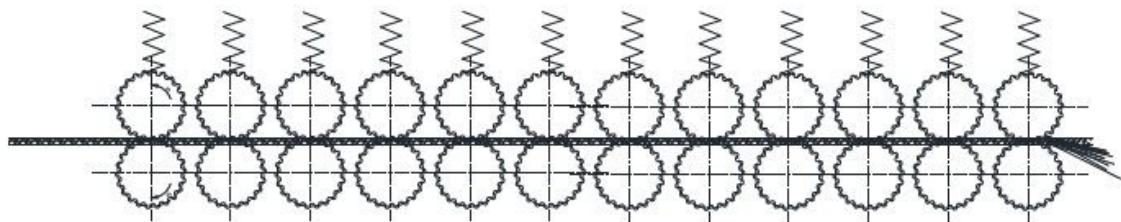


Figure 2

Schematic diagram of directional fiber opening of bamboo

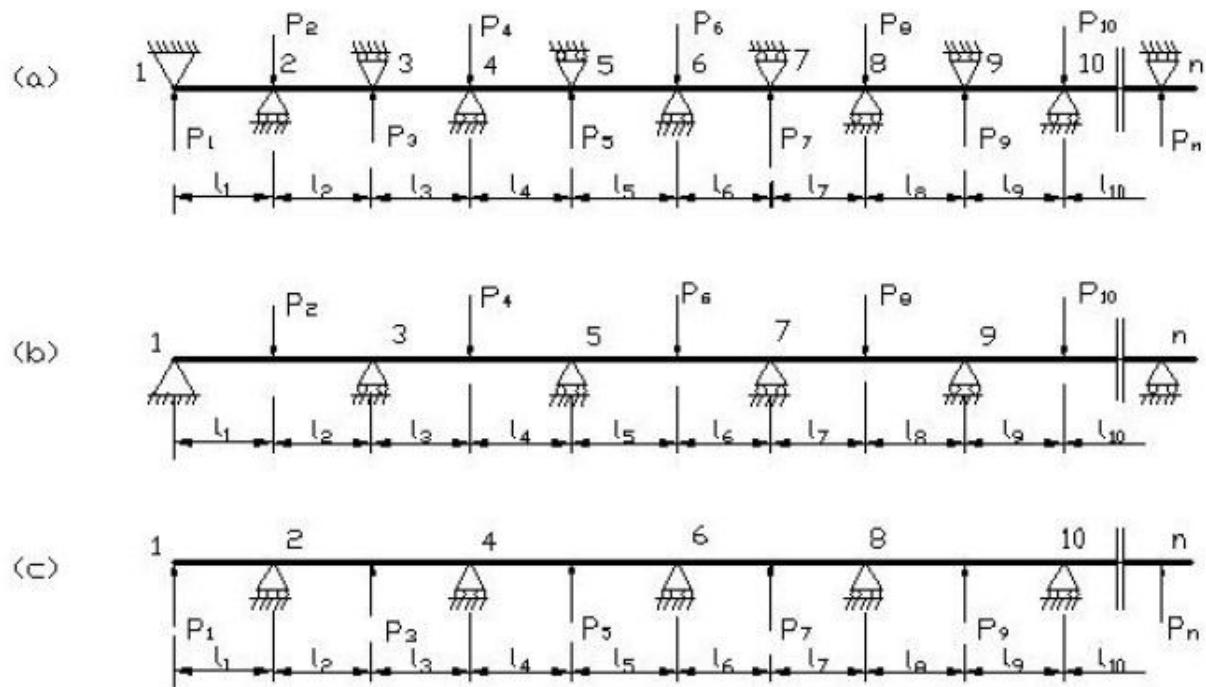


Figure 3

Schematic of bamboo rolling opening and its virtual beam calculation

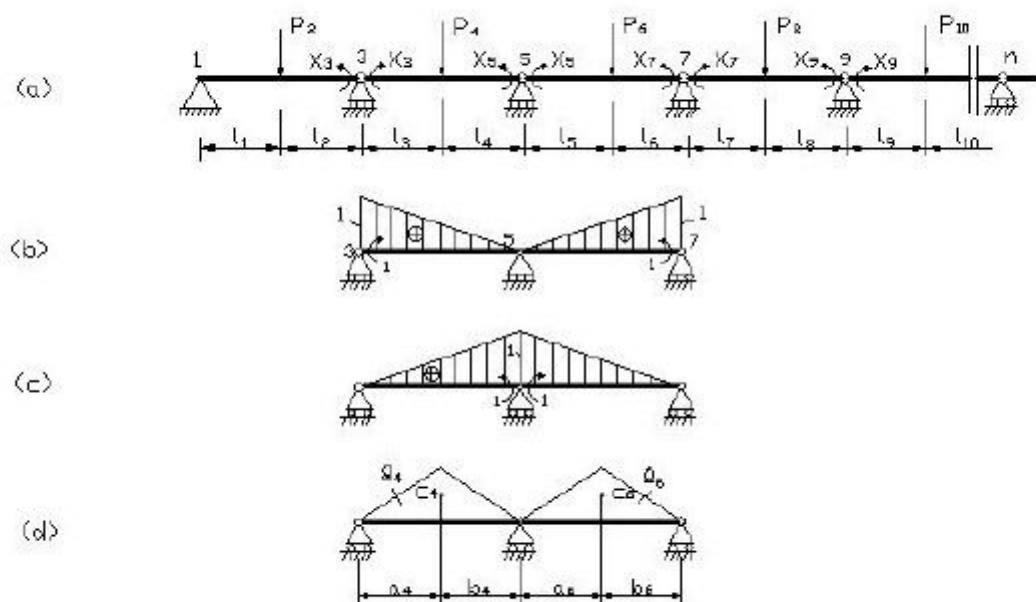


Figure 4

virtual beam 1 solution

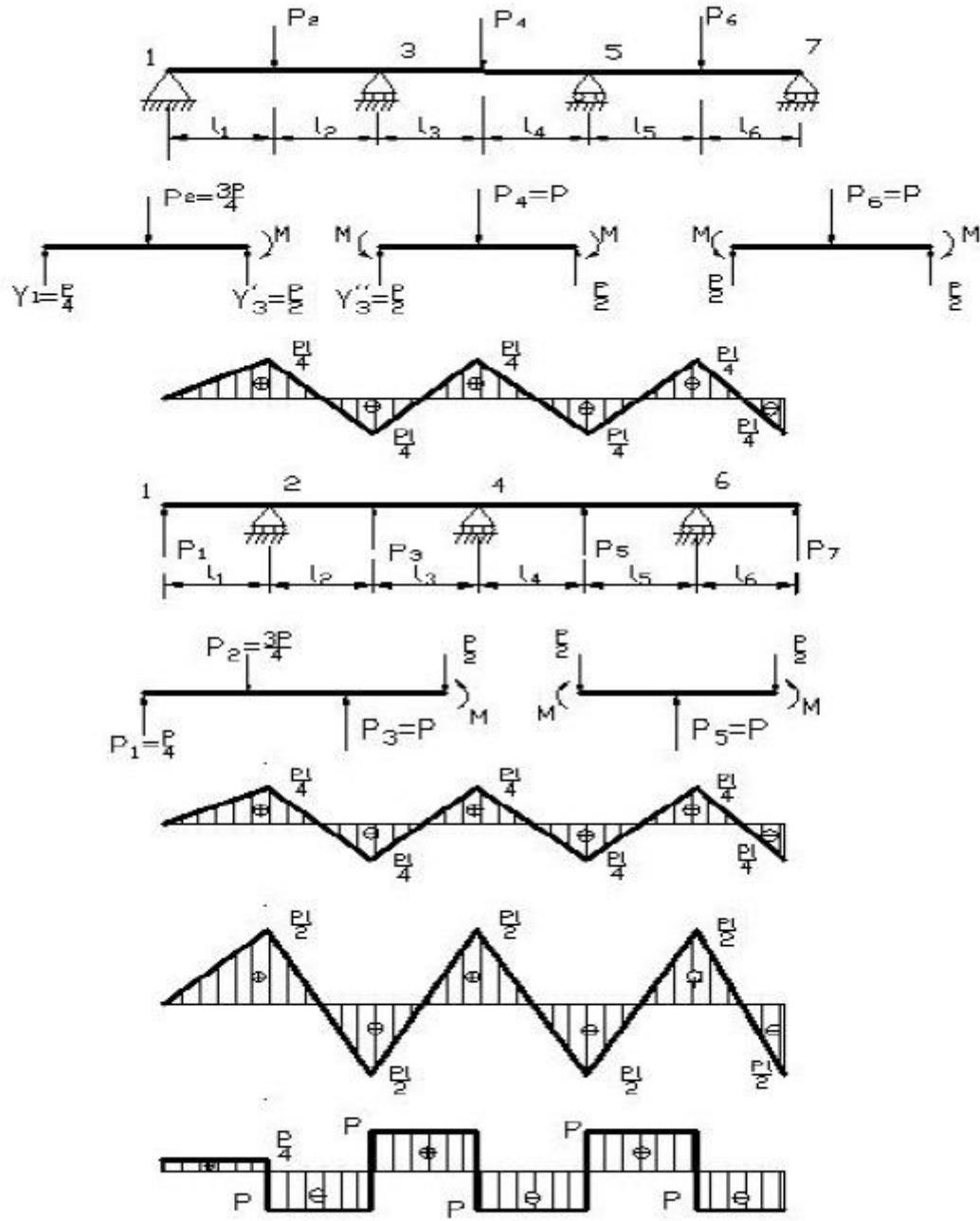


Figure 5

Bamboo strip continuous beam solution



(a)



(b)

Figure 6

End face of bamboo specimen in bamboo opening test