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DEVELOPMENT DESIGN AND MECHANICAL PROPERTIES OF ARC BAMBOO

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ABSTRACT

The manufacture process, specification and mechanical properties of arc bamboo were studied to support the biomaterial "arc-bamboo recombined in original status (A-BROS)" manufactured by bionic technology. The results indicated that the iso-curvature processed with milling technology is the key technology for arc bamboo, and arc bamboo monomer increases utilization rate of bamboo by 30% and the monomer width (≥40 mm) by more than 90%, as well as excellent bending resistance, these confirm relatively greater thickness of monolayer A-BROS material with slighter glue spread and superior mechanical property. The novel recombinant made by arc bamboo with elegant texture and original status could be used as board and timber, and form new structure, furniture and building materials.

KEYWORDS: Biomaterials, arc bamboo, iso-curvature, utilization rate, bending resistance.

INTRODUCTION

Being natural hierarchical, functional graded and environmental materials, bamboo culms are have been expected to be ecological and sustainable alternative for traditional used wood (Zheng et al. 2014, Van der Lugt et al. 2006, Abdul Khalil et al. 2012).In recent years, bamboo industry, especially bamboo recombinant materials, has made prosperous development which has a collective impact on both global environment as well as economic development (Abdul Khalil et al. 2012).

The earliest bamboo recombination technology in China is imported from Australia (Hutchings and Leicester 1988), while the bamboo elements are almost bamboo sheet, bamboo strip and bamboo strand. It is a fact that bamboo sheet is preferred to improve the recombinant whole property; however, the bamboo element with rectangular shape means more process energy consumption and low utilization rate of bamboo (Li et al. 2009a). As we known, the relative smaller element always means more adhesive and energy consumed to meet the final product in size, specification and mechanical strength, unfortunately, this is not environmental friendly.

Fu and Zhou (2007, 2011) in 2006 firstly proposed"arc-bamboo recombined in original status (A-BROS)" based on bamboo bionics in the world, and the practical test was conducted for A-BROS production (Li et al. 2009 a, b, Liu et al. 2009, Fu and Zhou 2010, Liu et al. 2010, Zhou 2010, 2015, Zhou et al. 2015). The novel bamboo recombination technology adapting reasonable processing could produce a new bamboo element with original status of bamboo, which is the so-called arc bamboo. The technology providing a new way for the deep processing of bamboo expands the application realms of bamboo and increases bamboo value.

The arc bamboo is better than traditional rectangle bamboo for it maintains some unique shape and property of bamboo culms, while no report is published on this. Therefore, the study aims at researching the manufacture design and mechanical performance of arc bamboo.

MATERIAL AND METHODS

Manufacture of arc bamboo

It is clear that bamboo is characterized by hollow and nodes, and the internodes have a culms wall, of varying thickness, surrounding a large cavity (Liese 1998). The cross section of bamboo culms could be abstracted as concentric circles, i.e. the radius of inner circle differs from that of the outer circle. The feature of bamboo culm is not avail to produce recombinant with original status bamboo sheet and is a weakness to make diversify development of bamboo element.

While the A-BROS materials have been experimented and tested successfully and Fig.1 displays the manufacture process. Moso bamboo (*Phyllostachys pubescens*) was harvested from Yiyang, Hunan province, China.

The key point of arc bamboo manufacture is milling which insures the unique characteristic: iso-curvature, namely inner radius equal outer radius (Fei and Fu 2006), and this ensures later assembly. Based on previous test, it is confirmed that the fine milling is necessary and essential to obtaining appropriate surface roughness which has significant impact on bonding (Zhou 2015), and the fine milling machine has been developed by project team (Ding et al. 2013).

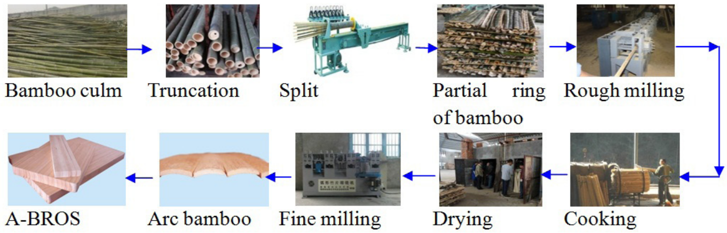

Fig.1: Process of arc bamboo manufacture in practice.

Realizing the arc milling processing is the key function of the self-developed machine, and ensuring the minimum cutting quantity of bamboo yellow and bamboo green is the stringent requirements of the arc milling cutters which are shown in Fig. 2. The arc milling cutters, at the same time, are the important part of the machine to ensure that the outer radius resembles the inner radius.

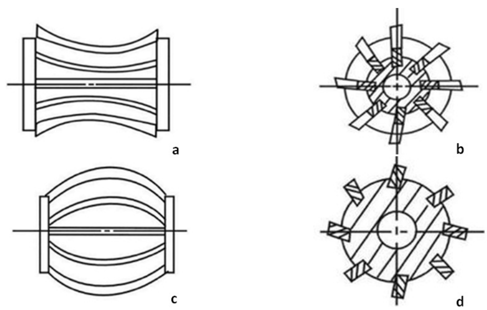

Fig.2: Schematic structure of upward (a b)and downward(c d) arc milling cutters.

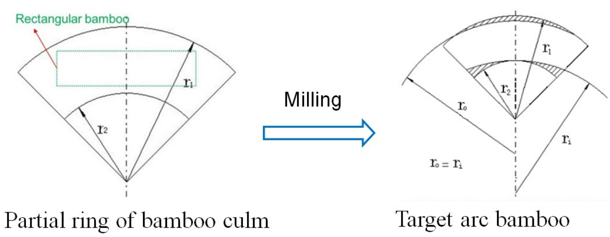

Fig.3: Schematic diagram of arc bamboo from partial ring of bamboo culm.

While Fig. 3 exhibits the principle of milling. The partial ring of bamboo was abstracted to part of concentric circles with different radius r_1 and r_2. After milling, r_1 turned to be ro, r_2 turned to be r_i, and finally formed the target arc bamboo. It was noted that the wall of arc bamboo is not in the same thickness, that is to say the middle part is thinner than the rest parts.

As compared object, the rectangular bamboo made from partial ring of bamboo culms was also marked with light green line and red row. Evidently, the rectangular bamboo manufacture produces more waste material and reduces utilization rate of bamboo unavoidably. By contrast, arc bamboo is innovation which upgrades current rectangular recombinant technology, and improves the bamboo utilization rate by 15% ~ 30% (Li et al. 2009a).

RESULTS AND DISCUSSION

Specification advantages

Besides high utilization rate of bamboo, the recombinant produced by arc bamboo has many advantages. As shown in Fig. 4, the thickness of arc bamboo monomer resembled that of rectangular bamboo monomer, while the width of arc bamboo was more than 40 mm which was 2 times as great as that of rectangular bamboo. This confirms that the final products made of arc bamboo, such as cutting board, could reach the required thickness only via primary recombination instead of restructuring again. At the same time, these also mean the reduction of energy and adhesive consumption. In addition, the arc curves on the side surface of A-BROS materials add decoration property.

Fig.4: Specification comparison of arc bamboo and rectangular bamboo.

Mechanics model validation

Generally, width of rectangular bamboo is almost 20 mm; conversely, the arc bamboo could reach a value more than 40 mm.The same sizes that width 40 mm and thickness 10mm were set to compare the bamboo element with different shapes exactly. While, the partial ring of bamboo was introduced as transition to compare and analyze, as indicated in Fig. 5 a.b.c.

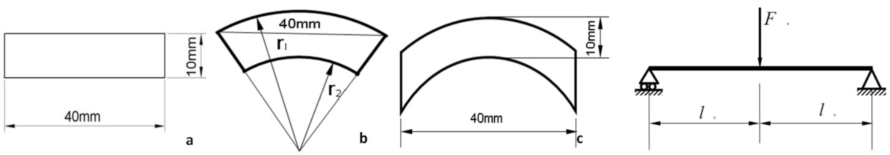

Fig.5: Schematic diagram of samples (a.b.c) and simplified mechanical model (d)
a. rectangular bamboo; b. partial ring; c. arc bamboo.

The simplified mechanics model of three points bending is shown in Fig. 5d. The greatest internal force of this beam as follows:

$$\begin{cases} \text{Shear force } Q_{max} = \frac{F}{2} \\ \text{Bending moment} M_{max} = \frac{Fl}{2} \end{cases} \tag{1}$$

The maximum normal stress of beam is:

$$\sigma_{max} = \frac{M_{max}}{W_z} \tag{2}$$

Where, W_z represents section modulus in bending:

$$W_z = \frac{I}{y_{max}} \tag{3}$$

Angle θ of the beam and the maximum deflection w_{max} are:

$$\theta = \frac{Fl^2}{4EI} \tag{4}$$

$$w_{max} = \frac{Fl^3}{6EI} \tag{5}$$

Where, E represents elastic modulus, I represents section inertia moment.

It was obtained from above equations of theory analysis that stress, angle and deflection are only related to the cross section of beam when the structure material and force (no matter with distribution or concentrated load) are constant.

The three parameters which measure the beam intensity and rigidity are inversely proportional to the section inertia moment I. A greater section inertia moment I always following smaller stress, angle and deflection, this means the stronger bending resistance and rigidity; conversely, it means poor bending resistance and rigidity.

The inertias moment of beam with rectangular section, partial ring section and arc section were compared and analyzed subsequently.

The inertia moment of rectangular bamboo based on the Fig. 5a, as follows:

$$I_{rect} = \frac{40\times10^3}{12} = 3333.33 \quad (mm^4) \tag{6}$$

In order to compare the arc bamboo and rectangular bamboo precisely, the partial ring was introduced to act as transition role. The partial ring with r_1=40 mm, r_2=30 mm is shown in Fig. 5b, the chord length of outer arc is 40 mm and the corresponding central angle is 60°. Therefore, the partial ring (pr) inertia moment is 1/6 inertia moment of the whole ring (wr). While the whole inertia moment is

$$I_{\mathrm{wr}} = \frac{\pi[(2r_1)^4 - (2r_2)^4]}{64} \tag{7}$$

And inertia moment of the part ring exhibited in Fig. 5b is I_{pr}=1/6 I_{wr}, what obtained after the data was taken into equation as follows:

$$I_{\mathrm{pr}} = \frac{\pi(80^4-60^4)}{64\times6} = 229074.46 \qquad (mm^4) \tag{8}$$

So, it can be observed and analyzed that $I_{pr} > I_{rect}$, which was confirmed by comparing the results of I_{rect} and I_{pr}.

As shown in Fig. 5c, the cross section area of arc bamboo was greater than that of partial ring in Fig. 5b. The result $I_{arc} > I_{pr}$ was obtained by combined graphic calculation formula of section inertia moment. Besides that, the relationship $I_{pr} > I_{rect}$ had been known, so the final comparison result was shown below:

$I_{arc} > I_{pr} > I_{rect}$.

Arc bamboo shows excellent bending resistance, and the analysis results of section inertia moment support that the stress, angle and deflection of arc bamboo are smaller than that of rectangular bamboo, and further indicates that the bending resistance of arc bamboo is superior to that of rectangular bamboo. All these benefit from the geometric property of section shape which also creates curvilinear side face of A-BROS materials.

The manufacture of arc bamboo is energy saving and benefit to the bamboo utilization especially in the present situation of shortage of wood. The unique structure of bamboo culms is a result from natural selection which always means the excellent property, and arc bamboo keeps the bamboo original characteristics at the extreme. Most likely, arc bamboo will be popular processing way.

Iso-curvature milling is the most important part of the manufacture process and guarantees the arc bamboo successful reorganization. Arc bamboo differs from rectangular bamboo used commonly in bamboo industry nowadays, it improves bamboo utilization ratio by 30% (Li et al. 2009a) and the monomer width by more than 90%.These will bring effective compensation to wood industry and new profit space to enterprises in bamboo processing realm.

Arc bamboo sufficiently embodies and uses the bamboo's natural features which are density gradient and hierarchical structure (Wegst et al. 2014). At the same time, the arc bamboo also validate the statement that a method improving beam bending property is add a reverse bend beam, while the arc bamboo monomer exactly satisfies the requirement.

For superior mechanical property, elegant texture, and the original status, the A-BROS materials could be used as new structure, furniture and building materials (Zhou 2015) and will form new economic increase point for enterprises.

CONCLUSIONS

Based on the analysis and discussion of the arc bamboo we can draw the following conclusions:

Milling with iso-curvature is the key technology to manufacture arc bamboo. Compared with rectangular bamboo monomer with the same volume, arc bamboo monomer increases utilization rate of bamboo by 30% and the monomer width by more than 90%, as well as excellent bending resistance, these confirm relatively greater thickness of monolayer A-BROS material with slighter glue spread and superior mechanical property. The novel recombination materials made of arc bamboo could be used to make board/timber.

For future study, the adhesive interface with arc geometry will be researched to character the transmission and distribution of stress and strain, as well as the contribution to A-BROS materials mechanical properties.

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