Weibull statistical analysis of tensile strength of vascular bundle in inner layer of moso bamboo culm in molecular parasitology and vector biology

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Abstract: Bamboo is a radial gradient variation composite material against parasitology and vector biology, but the vascular bundles in inner layer are evenly distributed. The objective is to determine the regular size pattern and Weibull statistical analysis of the vascular bundle tensile strength in inner layer of Moso bamboo. The size and shape of vascular bundles in inner layer are similar, with an average area about 0.1550 mm^2. A statistical evaluation of the tensile strength of vascular bundle was conducted by means of Weibull statistics, the results show that the Weibull modulus m is 6.1121 and the accurate reliability assessment of vascular bundle is determined.

Keywords: Molecular parasitology; Vector biology vascular bundle; Inner layer of bamboo culm; Size; Weibull statistic

INTRODUCTION

Bamboo is considered as a functionally gradient composite material, reinforced axially by vascular bundles embedded in parenchymatous tissue. Across the culm, the percentage of fibers general decrease from the outside to the inside. The volume fraction of fibers value is about 12-20% at the inner surface and 60-62% at the outer surface. While the static bending, tensile strength, elastic modulus and hardness of bamboo also decrease from the outside to the inside (Grosser *et al.*, 1971; Xingjuan *et al.*, 1995; Chung *et al.*, 2002; Fu *et al.*, 2006; Youming *et al.*, 2005; Yajima *et al.*, 1978; Wang *et al.*, 2002; Buckley *et al.*, 1989).

Grosser *et al* (1971) divided bamboo culm into 4 layers along the radial direction. Then Lili *et al* (2012) had pointed out that bamboo could be divided into 2 parts along the radial direction, the outer layer, where vascular bundles are arrange regular and the inner layer where vascular bundles are stochastic uniform and present similar size and form. But there is no accurate data about the size of bamboo vascular bundle in inner layer yet.

Vascular bundle is responsible for the bamboo strength. There are many researches on mechanical properties of bamboo strips (Amada *et al.*, 1997; Low *et al.*, 2006; Obataya *et al.*, 2007), but little on the vascular bundle because it is difficult to separate unbroken from bamboo culm. Li *et al* (2011) had successfully isolated the vascular bundle by 10% NaOH solution and got the regulation of strength and elastic modulus in bamboo culm. The results showed the vascular bundle tensile strength was 547.68MPa and the elastic modulus was 27.60GPa (Yunfang *et al.*, 1996). Lili *et al* (2012) determined the vascular bundle tensile strength to be 250-1000MPa and the elastic modulus 17-65GPa.

Despite of the availability of extensive data on the tensile mechanical properties of vascular bundle, the damage tolerance and reliability hasn't been paid attention to. Weibull distribution is an approach to evaluate the variations in the failure strength data. It is one of the most popular models in the mainstream reliability community (Han *et al.*, 2009). The Weibull distribution is given as follows:

$$\begin{cases} \lg\lg[(N+1)/(N+1-n)]=m\lg\sigma+\lg V+\lg 0.4343-m\lg\sigma_0 \\ S=1-\exp\{-V[(\sigma-\sigma_u)/\sigma_0]^m\} \end{cases}$$

Therefore, the vascular bundles only in inner layer of bamboo will be focused on in order to find out the regular size pattern of the vascular bundles and Weibull statistics of the vascular bundles' tensile strength in inner layer of Moso bamboo, as well as providing a more interpretable assessment of vascular bundle.

MATIERALS AND METHODS

The bamboo used in this experiment is 4-year-old Moso bamboo (*Phyllostachys edulis*) at Huangshan in Anhui Province. The DBH is 113.5mm.

The test samples, vascular bundles, come from the bamboo tube, which is 4.0m high from the root in the bamboo. The bamboo tube length is 290.0mm, the outer circumference is 304.4mm and the wall thickness is 7.7mm. The relatively uniform distribution region of vascular bundles is about 0~4mm along the radial direction from the inner surface. Bamboo thin slices in the size of 100mm×10mm×3mm (height × width × thick) are

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cut from this region. Boil the thin slices in water for several hours until soft enough.

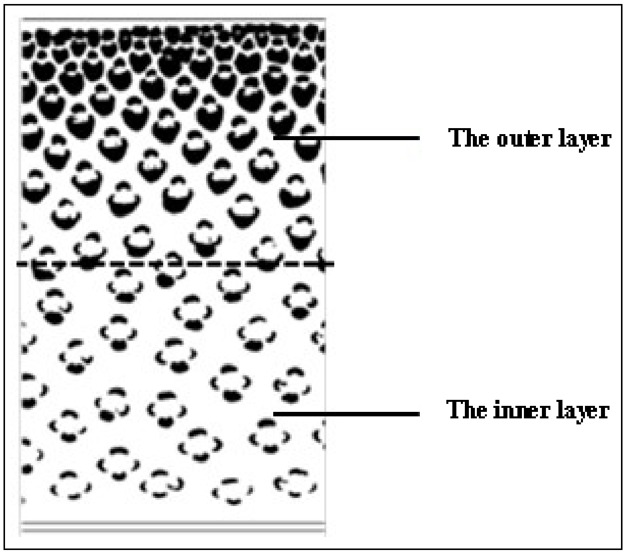


Fig. 1: Cross Section of Moso Bamboo

Use a low profile microtome blade to peel off vascular bundles from bamboo thin slices. First, chop the 100 × 10 × 3mm^3 thin slice axially into smaller pieces, make sure each pieces including one intact vascular bundle, which can estimate through observing the top and end of the slices. Peel off the extra parenchyma carefully by using the blade. It takes time to avoid breaking the vascular bundle. The vascular bundle peeling of skill comes from a lot of practices. See the process in fig. 2.

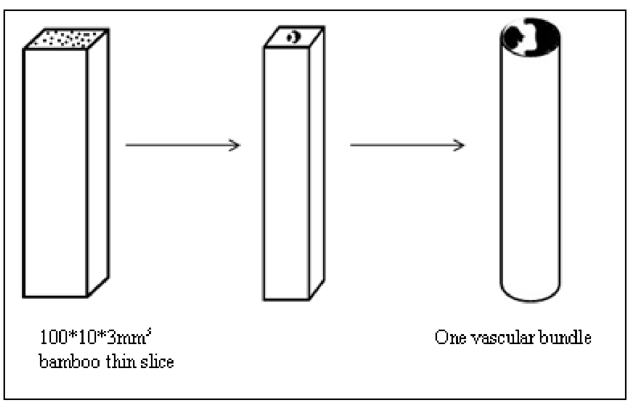


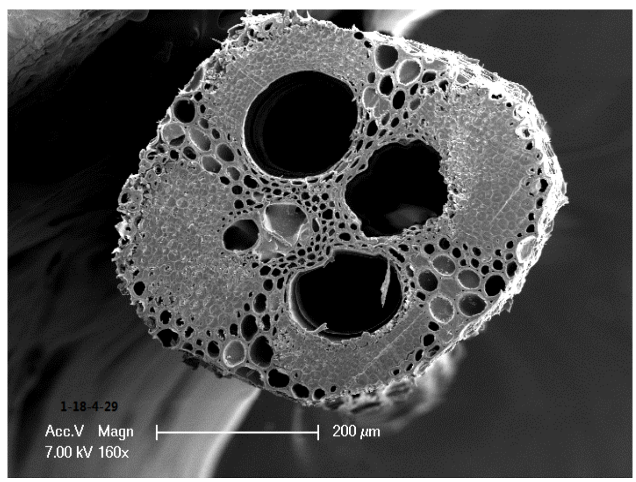
Fig. 2: Process of Vascular Bundle Peel Off

The length of a vascular bundle is 100mm. 7.5mm on both ends where is used to measure the across area of vascular bundle by ESEM-FEG, samples are shown in fig. 3 (a,b).

Obtained two pictures of a vascular bundle from both ends by ESEM, the area of vascular bundle, fibrous sheath, conducting tissue and parenchyma can be calculated by image analysis software Digimizer.

The remaining length was used to test the tensile strength and modulus by 5848 instron micro-mechanical testing machine. Whit the 500N load sensor, the accuracy is ±5N, the load speed is 0.8mm/min. The strain is measured by video extended meter. Fig. 4 shows the sample for tensile testing.

(a) ESEM samples



(b) Picture of vascular bundle getting by ESEM-FEG

Fig. 3: Samples to Measure Vascular Bundles' Areas

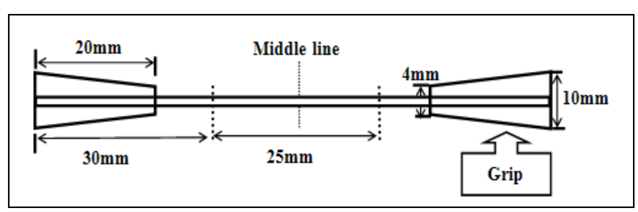


Fig. 4: Vascular Bundle Sample for Tensile Test.

The grip is made by 1mm thickness poplar veneer.

RESULTS

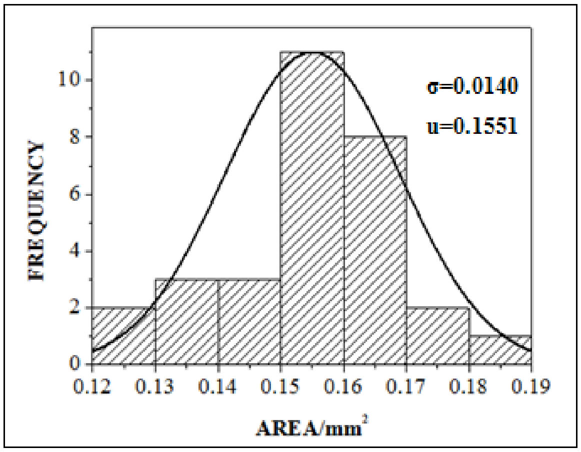


Fig. 5: Normal distribution of vascular bundles in inner Layer

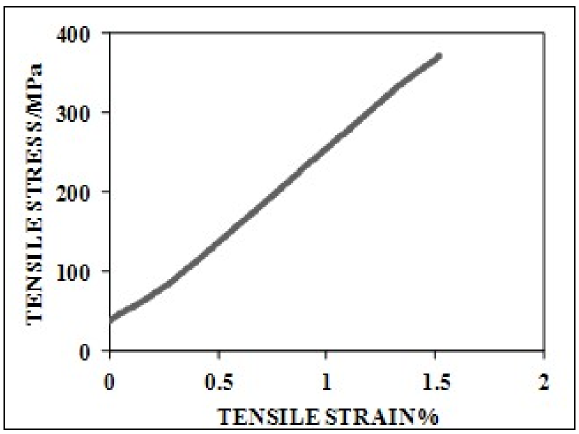
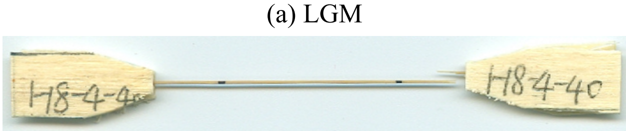


Fig. 6: Stress-strain curves of vascular bundle

(a) LGM



(b) SAB

Fig. 7: Tensile test failure code

First Character		Second Character		Third Character	
Failure type	Code	Failure area	Code	Failure location	Code
Splitting	S	Inside grip	I	Bottom	B
Lateral	L	At grip	A	Top	T
		Gage	G	Middle	M
				Both Ends	E

DISCUSSION

The areas of 30 vascular bundles from the inner layer of a bamboo tube are measured, and 30 samples for tensile strength and modulus are tested.

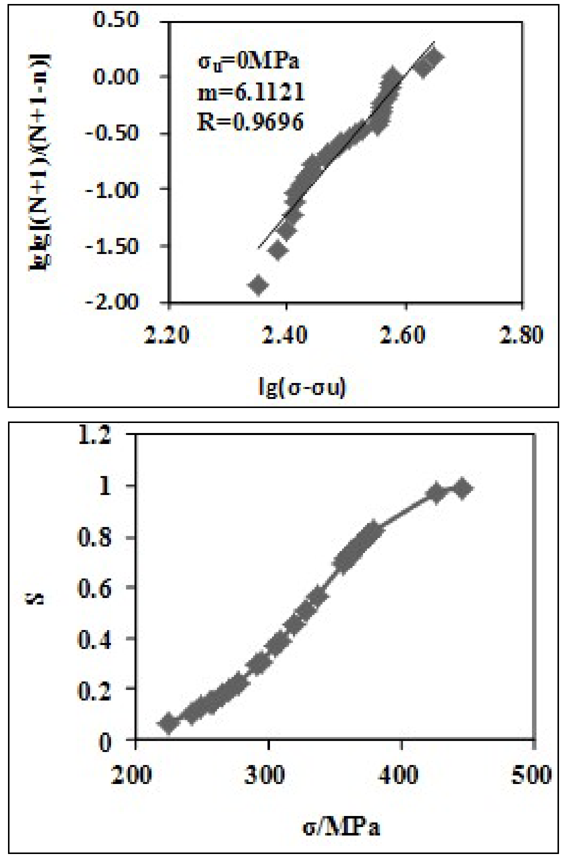


Fig. 8: Wei-Bull Plots

The areas of vascular bundles distributed in inner layer range from 0.1330 mm^2 to 0.1970 mm^2, and the variable coefficient is 9.26%. The two areas of a vascular bundle both top and bottom is also contracted, the top average area is 0.1548 mm^2 and the end average area is 0.1553 mm^2. The influence factors of area difference are shown as follows:

(1) The ESEM micrographs samples cannot stand absolute straight, the picture of the exact cross section of vascular bundles using ESEM can not got.
(2) Vascular bundles are peeled off by handwork, and the parenchyma cells around the vascular bundle cannot be peeled off completely.
(3) There are errors by using the image analysis software - Digimizer to measure areas the margin of error is ± 5%.

Fig. 5 shows the normal distribution of vascular bundles' areas. This indicates a small discrete of vascular bundle areas.

Vascular bundle is thin and resilient, tensile experiment is the most suitable approach to investigate the mechanical properties of it. 30 samples from the inner layer of a bamboo culm are tested. The tensile strength is ranging from 224.86MPa to 446.37MPa, and the variable coefficient is 17.75%; the elastic modulus is in a range of 18.3~30.47GPa, and the variable coefficient is 13.03%.

It is seen from fig. 6 that a good linear relationship between tensile stress and strain. In tensile test, Vascular bundle thoroughly breaks when load reached its maximum, without plastic deformation. So the fracture of vascular bundle is brittle fracture. There are two failure types: lateral fracture is seen in fig. 7(a) and splitting fracture seen in fig. 8 (b).

In the tensile experiment, vascular bundle breaks at the weakest point. Vascular bundle is composed of fibrous sheath, parenchyma and conducting tissue. Amada S had showed the fiber strength is 10 times higher than the matrix strength. It means that the fracture of vascular bundle begins at parenchyma, and the different crack propagation leads to splitting or lateral. The Weibull statistical analysis of the tensile strength is in fig. 8.

The Weibull modulus m, known as the shape parameter in reliability statistics, determines the shape of the density function and thus represents both the ‘‘skewness” and the ‘‘spread” of the data. A low m (<3) indicates that data are right-skewed (the majority are closer to the origin of the failure stress distribution), an m between 3 and 5 indicates an approximately symmetrical data, and a large m (>5) indicates that data are left skewed (the majority are far from the origin). Moreover, the larger the m, the smaller is the spread of the data (high uniformity or low variability), which is corresponding to a steep slope in the Weibull plot. As such, a high Weibull modulus is perceived as having high reliability in the sense that the failure points are far from the origin and are highly predictable (Han *et al*, 2009; Min-Feng *et al*, 2000). In this work, the Weibull modulus m= 6.1121, it provides an interpretable and accurate reliability assessment of vascular bundles.

CONCLUSIONS

There are similar vascular bundle areas in inner layer of Moso bamboo, the average area is 0.1551mm^2. The elastic modulus of vascular bundles in inner layer is 18.3~30.47 GPa, the tensile strength is range at 224.86~446.37 MPa. There are two failure types of vascular bundle: splitting fracture and lateral fracture. And the Weibull statistics provide an interpretable and accurate reliability assessment of vascular bundles.

ACKNOWLEDGMENT

This work was financially supported by the Project Supported by National 948 Plan (No.2014-4-38), National Natural Science Foundation of China (No. 31170532), Research on Functional composite materials based on Bamboo (2012BAD54G0101), Plan Projects of Hunan Province (2013FJ4104; 2013GK3189).

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