Damage of bamboo and wooden materials based on linear elastic fracture mechanics in garden design

Tang Haiyan
City College of Science and Technology.Chongqing University, Chongqing, 402167, China
tanghaiyan23@sina.com

ABSTRACT. Bamboo and wood are the most widely applied and the oldest natural structural materials in the world. Currently, worldwide output of wooden material is 1 billion ton, almost the same as steel. Most of them are used as structure, such as load carrying girder, scaffold, floor and support. Wooden materials and bamboo materials with clear microstructure are composite biomaterials which can be studied under multiple scales. Irregular evolution behaviors of initial defects or damage during loading determines macro mechanical behavior of wooden and bamboo materials. Taking wood and bamboo as test materials, this study explored mechanical characteristics and damage crack behavior of wood and bamboo as well as toughening mechanism.

KEYWORDS. Wooden material; Bamboo material; Damage and crack; Strengthening and toughening mechanism.

INTRODUCTION

Wood and bamboo with special garden aesthetic features play significantly important roles in classical or modern garden landscaping. Wood and bamboo are natural structural materials which are the oldest and the most extensively applied worldwide. Long before, people have used bamboo to build bamboo house and make scaffold and bamboo ladder. Thus it is of great significance to study strength of natural structural materials and understand damage behavior for design and safety evaluation of bamboo and wooden structure. Mechanism of crack of materials and how to control occurrence of crack incidents are always being explored by material science researchers and engineering technicians [1].

He et al. [2] replaced bamboo joint with equivalent crack length Lc which stands for the length of crack produced by clear specimen bearing a stress the same as which results in initial cracking on burl specimen, but the method is only applicable for cross grain tensile loading. Shao [3] proved that crack expanded in a direction that is vertical to notch, even under parallel-to-grain stress. Moreover, Deng et al. carried out a study on type I crack on two hard woods and softwoods using acoustic emission monitoring device. Someone has also found that old wooden material is easier to produce small amplitude acoustic emission signal compared to new wooden material [5]. Ying et al. [6] once explore physical mechanical properties of bamboo, and Yong et al. [7] compared banding property between bamboo and wood. Compared to crack of

wood, research on crack of bamboo is fewer. Only Amada et al. [8] has studied transverse bending crack of bamboo and pointed that could be used as structural material because of its well-matched toughness and strength of cross grain crack.
To select out bamboo and wood suitable for garden landscaping and explore damage crack behavior and toughening mechanism of biomaterials comprehensively, this study performed theoretical derivation in combination with experiment to study damage crack mode of different kinds of woods and bamboos.

LINEAR ELASTIC FRACTURE MECHANICAL CHARACTERISTICS OF WOOD

Crack and defect are inevitable in engineering materials. They produce either in production process, processing process or using process. For example, fatigue crack, compressive injury, ring shake and radial shake will generate under alternating force [9]. To conveniently study strength of cracked body, we classify cracks into three categories, opening mode (mode I) produced under external normal stress, sliding mode (mode II) produced under shear stress parallel to crack direction and tearing mode (mode III) produced under stress that can stagger crack surface, according to stress and characteristics of crack (Fig.1).

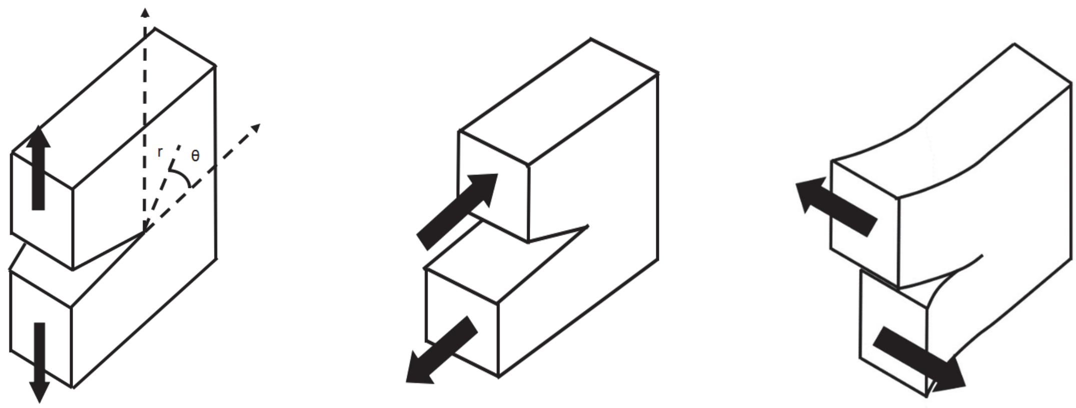


Figure 1: Illustrations for mode I, mode II and mode III crack.

Particularity of application of linear elastic fracture mechanics in wood

Wood is an anisotropic and heterogeneous material. Stress-strain curve of wood in different loading form is linear, consistent with linear elastic behavior [10]. Its three elastic symmetry planes are vertical to length wise direction (L), radial direction (R) and tangential direction (T). Thus, if we use the first symbol to express the normal direction and the second symbol as expansion direction of crack, then there are six kinds of crack growth forms, i.e., TL, RL, LT, LR, TR and RT, as shown in Tab. 1.
Orthotropic materials usually have more complicated crack than isotropic material [11]. We derive equations for stress and displacement field of crack tip of orthogonal anisotropic material using complex variables functions [12].

$$\sigma_{ij} = \frac{K}{\sqrt{2\pi r}} \cdot \mathrm{Re}\left[f_{ij}(\theta,\alpha,\alpha_{ij},u_1,u_2,u_3) \right]$$
$$v_{ij} = \frac{K}{G} \cdot \sqrt{\frac{2r}{\pi}} \cdot \mathrm{Re}\left[f_{ij}(\theta,\alpha,\alpha_{ij},u_1,u_2,u_3) \right] \quad (1)$$

where a_{ij} is elastic constant of material; u_l, u_2 and u_3 are compound parameters of materials which are determined by degree of anisotropy and angle α between crack and long grain fiber (Fig. 2) and Re is real part of complex function f_{ij}.

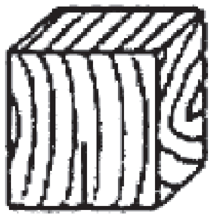
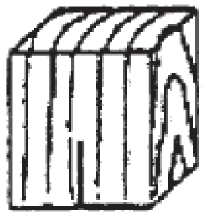
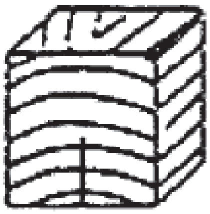
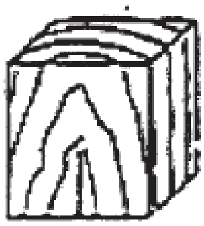
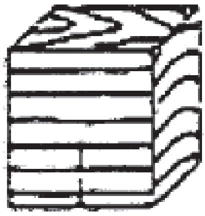
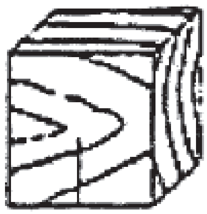
	R	T	L
R			
T			
L			

Table 1: Classification extension of wood basic crack.

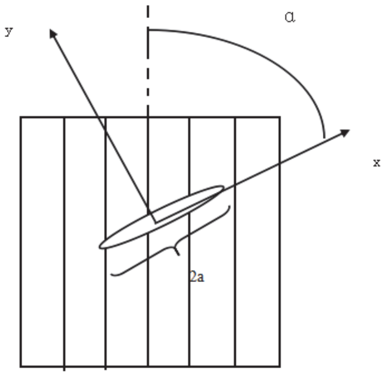


Figure 2: Illustration for direction of crack and fiber.

It can be found from the above equations that, crack of orthogonal anisotropic material is much more complicated than isotropic material. The differences are as follows.

First, crack of orthogonal anisotropic material expands in the direction of fiber rather than the initial direction. But linear elastic fracture mechanics presupposes that, crack always expands in the initial direction [13].

Secondly, even if under a simple-form loading, crack tip of orthogonal anisotropic material can also displace in a compound way, which is different from linear elastic fracture mechanics principle based on distinction means of mode I, II and III.

Stress field of crack tip of orthogonal anisotropic material is a function with regard to composite parameters of materials, and meanwhile these parameters are a function with regard to material property and angle α between crack and fiber direction. It is also different from linear elastic fracture mechanics principle that develops from the statement that stress distribution of crack tip is in no correlation to property and direction of material texture.

Based on the above facts, linear elastic fracture mechanics theory is not applicable to orthogonal anisotropic material. That is because we cannot define crack toughness of orthogonal anisotropic material with three material constants K_{IC},

K_{IIC} and K_{IIIC}, unless investigate every condition when crack and fiber direction have any fixed angle and test applicability of linear elastic fracture mechanics under all condition, but the operation is inconvenient and even impossible [14]. However, if the initial direction of crack is consistent with fiber and principal axis of orthotropy is coincident with crack surface direction and crack growth direction, all derivation with linear elastic fracture mechanics theory mentioned above can be eliminated. That is because many experiments have verified that, crack expands in initial direction which is consistent with direction of fiber; displacement is no longer compound; composite parameters of materials are constants under the condition of fixed crack and fiber direction (a=0), thus stress distribution of crack tip is only a function with regard to r and θ.

The above three situations suggest that, theory of linear elastic fracture mechanics is applicable for crack whose direction is consistent with fiber. Most cracks and defects formed in the growing period of tree and processing process are in the direction of fiber of wood, as the resistance to expansion of crack is the minimum in the direction of fiber. As TL crack growth is quite similar to radial shake and meanwhile RL crack growth is similar to ring shake, theory of linear elastic fracture mechanics is thought to be applicable for parallel-to-grain growth of crack of wood. Studying and measuring toughness which is a representation of resistance to parallel-to-grain cracking of wood is of important practical value for design of wooden structure and processing technique optimization.

PROCESS OF DAMAGE CRACK ON WOOD

Crack mechanics is a subject involving macro crack growth rule and quantitative analysis [15], but mechanical effects of inevitable microdefects which have existed before macro cracks are not included. In wood, a large amount of original microdefects such as pit, crack on cell wall and interface damage will gradually evolve or emerge into macro crack under load. Wood damage refers to mechanical property degradation induced by progressive decrease of internal cohesion resulting from microdefects formed under the effect of load or environment. It is an irreversible and energy-consuming process of internal microstructure. Macro cracks form when damage variable reaches extreme value. Damage evolution is the premise for formation of cracks and moreover crack growth expands the damage; therefore, damage and crack of wooden materials reflects a whole physical process from deformation to damage.

Materials, equipments and methods

This test is to explore the effect of defects on acoustic emission in the process of bending taking Picea jezoensis as test material. Picea jezoensis is made into two groups of specimens, i.e., standard group (wood without crack and in a size of 300(L) × 20(T) ×20(R) (mm)) and crack group (wood in a size of 300(L) × 30(T) × 20(R) (mm)). Wood in crack group is cut a 10 mm deep sharp crack along tangential direction to make a 20×20 (mm) net section on crack tip. Both groups include 30 specimens, 60 in total. Three-point bending load along tangential direction is used.

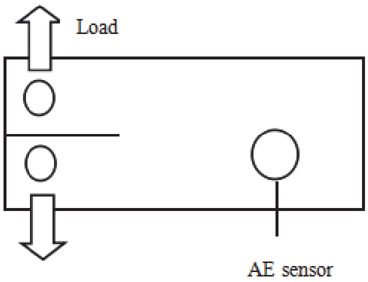
Equipments used in the test include microcomputer controlled material testing machine, AE-4 acoustic emission equipment [16] and R1 acoustic emission sensor.

Compared to other non-destructive testing technologies, acoustic emission technique has a distinctive character, that is, detected objects involve in the detection process actively. Based on the received acoustic wave and external conditions inducing acoustic wave, we can understand both the status of defects and formation of defects as well as growth tendency under practical condition [17]. Therefore, acoustic emission technology can be used in monitoring damage accumulation of materials in the process of deformation and failure, identifying failure mechanism and confirming damage site.

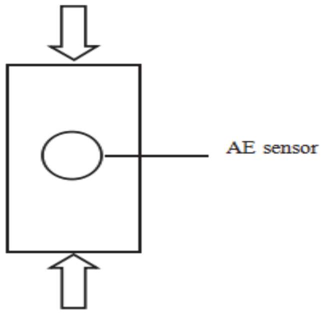
Experimental results and analysis

It is difficult to identify and distinguish acoustic emission signals derived from different damage mode in different stages of bending of wood. That is because, wood as a composite biomaterial with multiple unit structures usually has multiple kinds of deformation and damage which can change energy in the same stage in the process zone around crack tip. Therefore, we design a double cantilever beam on parallel-to-grain cracking and a compression test (Fig. 3). Mode I crack is found in the former test and the latter test only results in cell wall bending and collapse damage. Experimental results suggest that, parallel-to-grain cracking only leads to low amplitude and low energy acoustic emission event, whereas acoustic emission signal produced by bending and collapse even has lower energy.

We analyzed and summarized a large amount of acoustic signals from different wood samples and found that, peak amplitude Vmax in acoustic emission parameters and root mean square (RMS) of effective voltage can be used to identify different damage type, when sensor is put in a place less than 10 m away from damage source. RMS is more effective and it is directly correlated to energy released by acoustic emission events. Vmax and RMS under different condition are shown in Tab. 2.



(a) Double cantilever beam test



(b) Compression test

Figure 3: Illustration for double cantilever beam test (a) and compression test (b).

Category of damage		Bending and collapse of cell wall	Delamination splitting	Crack on fibre bundle	Tearing and fracture on cell wall
Vmax	mV	< 2	< 64	< 0.5	< 53
	dB	< 11	< 79	< 1	< 61
RMS	mV	< 34	< 90	< 11	< 81
	dB	> 34	> 90	> 11	> 81

Table 2: Acoustic emission characteristics of wood with different damage.

MECHANICAL CHARACTERISTICS OF BAMBOO STRUCTURE

Test samples

The ninth and twentieth joint of three-year moso bamboo were cut down and split into bars (200 mm×10mm) after air-seasoning. Then the bamboo was made into 60 tensile samples which was wide and thick on two ends and thick and thin in the middle. 60mm×5mm×1.5mm was the size of major section for testing. As the sample was cut from different radial position of bamboo, fibre bundle contained in the cross section was also different. 12.5% of the test sample was water and the experiment was carried out at 25 °C.

Simplified mechanical model and testing principle

Bamboo materials cut from parts between joints can be considered as evenly distributed and continuous fibre reinforced composite material, if they have small thickness. Bamboo fiber bundle is characterized by high strength and high modulus, while ground tissue of bamboo is just the opposite. Meanwhile, the fragment from the starting point to emergence of facture in stress-strain curve is a straight line, as shown in Fig. 4. Therefore, parallel model composing of two elements (bamboo fiber and ground tissue) can be used to describe mechanical behavior of bamboo. Deformation of two elements is assumed to be the same when carrying load.

F_c, F_f, F_m, σ_c, σ_f and σ_m are used to express force and stress that act on composite material, fiber and ground tissue. ε_c, ε_f, ε_m, E_c, E_f and E_m are used to express corresponding strain and elasticity modulus. Cross sectional area of bamboo fiber, ground tissue and composite material is set as A_f, A_m and A_c respectively. Usually, content of two elements is expressed with volume fraction V, i.e., load acting on bamboo samples is shouldered by bamboo fiber and ground tissue. Then we have:

$$F_c = F_f + F_m \tag{2}$$

or

$$\sigma_C A_C = \sigma_f A_f + \sigma_m A_m \tag{3}$$

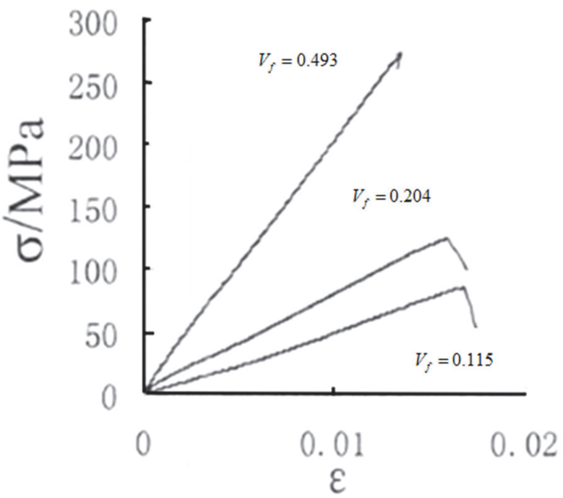


Figure 4: σ-ε curves.

Both sides of Eq. (2) are divided by A_c, and then we get:

$$\sigma_C = \sigma_f V_f + \sigma_m V_m \tag{4}$$

Strain is the same when bamboo is under stress.

$$\varepsilon_C = \varepsilon_f = \varepsilon_m \tag{5}$$

If we divide Eq. (2) with $\varepsilon_c A_c$, we get:

$$\frac{\sigma_C A_C}{\varepsilon_C A_C} = \frac{\sigma_f A_f}{\varepsilon_C A_C} + \frac{\sigma_m A_m}{\varepsilon_C A_C} \tag{6}$$

When load is within linear strain range, then correlation of elastic modulus E_c with elastic modulus and volume modulus of different element can be obtained.

$$E_C = E_f V_f + E_m V_m = E_f V_f + E_m (1 - V_f) \tag{7}$$

Eq. (3) and (6) can be called as mixture law for mesomechanics of composite materials [18].

Experiment and results

The samples were placed in self-tightening fixture of microcomputer controlled mechanical machine and the test section of samples was installed with extensometer whose gauge length is 50 mm. Then the force was loaded in a speed of 2 mm/min until fracture emerges. As ground tissue of bamboo, it has higher strength and modulus than bamboo fibre bundle, thus mechanical behavior of bamboo samples in tensile test is mainly determined by strength and rigidity of bamboo fiber bundle. Corresponding stress-strain curve (Fig. 4) shows up little or no non-linear deformation.

Small pieces cut from the position close to fracture was first placed into oven after being added with solution containing 10% glacial acetic acid and 10% hydrogen peroxide and then soaked for 2 or 3 days at 60 °C. Afterwards, it was cut into section in a thickness of 15 μm after being softened by alternated cooling and heating treatment in water [19], followed by staining, dehydration and transparent disposal. One or two hours later, the sections were embedded with neutral resins. Then the area of fibre bundle was observed under microscope. Tab. 3 demonstrates six layers of micro cross section (from inside to outside) and area of fibre bundle.

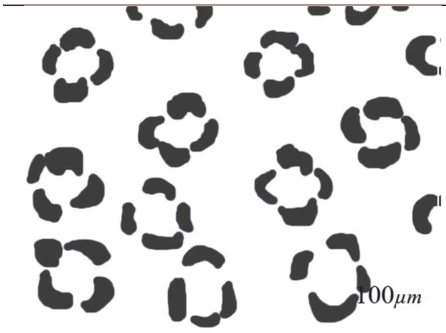
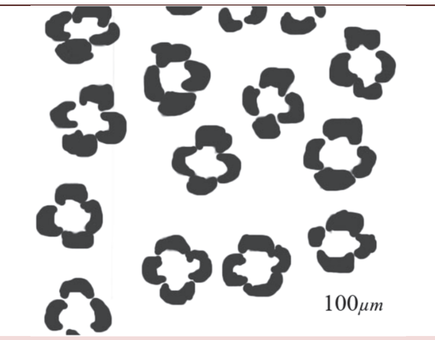
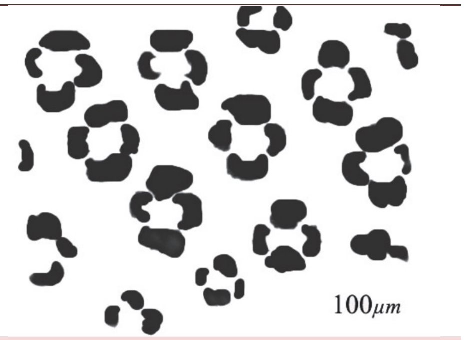
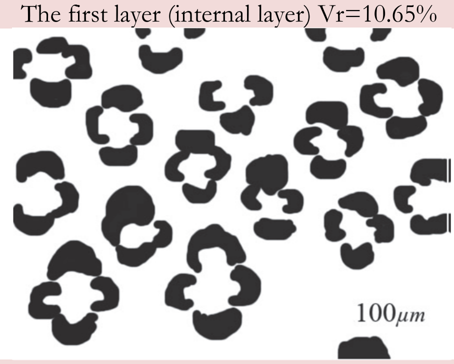
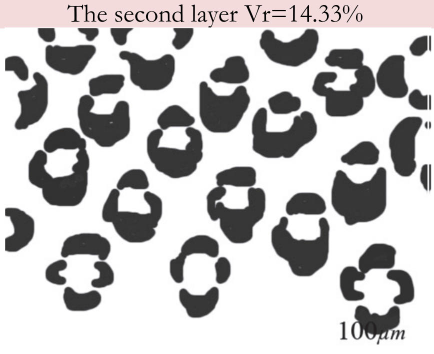
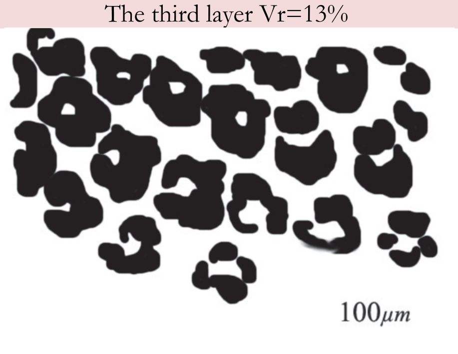
		
The first layer (internal layer) Vr=10.65%	The second layer Vr=14.33%	The third layer Vr=13%
		
The fourth layer Vr =27.3%	The fifth layer Vr =34.02%	The sixth layer (External layer) Vr=44.29%

Table 3: Six layers of micro cross section (from inside to outside) and area of fibre bundle.

Limiting stress and elastic modulus of every bamboo sample were calculated.

$$\begin{aligned} \sigma_c &= 562.69V_f + 19.042 = 588.732 - 562.69V_b \qquad (R = 0.936) \\ E_c &= 40.129V_f + 0.2219 = 40.351 - 40.129V_b \qquad (R = 0.955) \end{aligned} \tag{8}$$

Correlation between elastic modulus, tensile strength and volume fraction of fiber can be obtained when we correlate results obtained above and volume fraction of fiber together, as shown in Fig. 5 and 6.

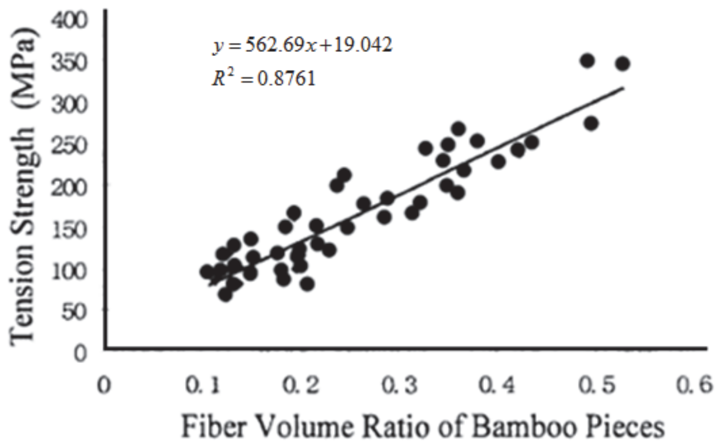


Figure 5: Correlation between tensile of bamboo strength and volume fraction of fiber.

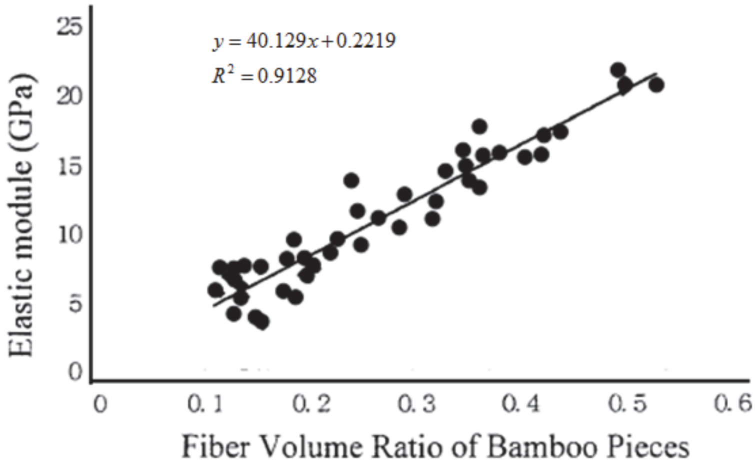


Figure 6: Correlation between elastic module of bamboo and volume fraction of fiber.

Both V_f and V_b were defined as 0. Then we obtained the tensile strength of bamboo fiber $\sigma_f = 588.732\text{MPa}$, tensile strength of ground tissue $\sigma_b = 19.042MPa$ and elastic modulus E_b=0.2219GPa based on Eq. (1). Thus we consider bamboo fiber is the main component bearing load and its strength is larger than general steel materials.

CONCLUSIONS

Under the effect of load, different mechanism associated with internal damage and crack of materials can induce different degrees of energy release, leading to abundant acoustic emission signals. Applying acoustic emission technology can help identify the emergence and extension of different types of damage produced on wood in the process of loading. Test results indicate the following three points. Firstly, defect-free samples have slowly developed acoustic emission events in the initial stage of loading, and acoustic emission signals that emerge in that period are of low amplitude; a large number of high-amplitude acoustic amplitude signals emerge when loading reaches the peck value or crack appears. Secondly, monitoring the damage of crack process of defective wood under three-point bending loading with acoustic emission can effectively identify initial stage of crack and extension stage. Thirdly, characteristics of acoustic emission signals are associated with damage mode of wood; acoustic emission characteristics regarding facture on cell wall is high-amplitude, high-energy and long-lasting, while acoustic emission corresponding to cell wall interface damage and spalling damage as well as cell bending and collapse damage is low-amplitude, low-energy and lasts for short time.

We tested and analyzed mechanical performance of bamboo samples cut from bamboo wall along radial direction and bamboo fiber bundle isolated from bamboo materials with rule of mixture and shearing-lag theory. We found strength and elastic modulus of bamboo cut from bamboo wall along radical direction was positively correlated with volume fraction of bamboo fiber. Fibre bundle of three-year moso-bamboo was detected to have 588.72 MPa tensile strength and 40.35Gpa elastic modulus and tensile strength and elastic modulus of ground tissue were 19.42 MPa and 0.222 GPa. Tensile strength and elastic modulus of single bamboo fibre bundle were detected to be 482.18 MPa and 33.85 GPa. Thus we draw conclusions that, ground tissue is capable of transferring loading and dispersing stress loaded by fibre bundle evenly and strength of bamboo fiber gathering in ground tissue is higher than isolated bamboo fibre bundle.

REFERENCES

[1] Duggan, T.V., Fatigue and fracture mechanics, Physics in Technology, 14(3) (1983) 126-132.

[2] He, W., Nakao, T., Yoshinobu, M., Treatment of fast-growing poplar with monomers using in situ polymerization, Part I: Dimensional stability and resistance to biodegradation, Forest Prod J, 61(2) (2011) 113-120.

[3] Shao, Z., Jiang, Z., The particularity of application of principles of linear-elastic fracture mechanics to wood and fracture parallel to grain, Scient Silv Sinic, 38(6) (2002) 110-115.

[4] Deng, H., Yuan, X., Li, J., Fracture Mechanics Characteristics and Deterioration Mechanism of Sandstone under Reservoir Immersion Interaction, Earth Sci, 39(1) (2014) 108-114.
[5] Ando, K., Hirashima, Y., Sugihara, M., Hirao, S., Sasaki, Y., Microscopic processes of shearing fracture of old wood, examined using the AE technique, J Wood Sci, 52 (2006) 483-89
[6] Ying, S., Wang, C., Lin, Q., Effects of heat treatment on the properties of Bamboo fiber/polypropylene composites. Fiber Polymers, 14(11) (2013) 1894-1898. DOI: 10.1007/s12221-013-1894-5
[7] Shi, Y.-D., Pan, L.-F., Yang, F.-K., A preliminary study on the rheological properties of human ejaculate and changes during liquefaction, Asian J Androl, 6(4) (2004) 299-304.
[8] Amada, S., Sun, U., Fracture properties of Bamboo. Compos Part B Eng, 32(5) (2001) 451‑459. DOI:10.1016/S1359-8368(01)00022-1.
[9] Yan, J., Taskonak, B., Platt, J. A., Evaluation of fracture toughness of human dentin using elastic-plastic fracture mechanics, J Biomech, 41(6) (2008) 1253-1259. DOI:10.1016/j.jbiomech.2008.01.015
[10] Shao, Z., Jiang, Z., The particularity of application of principles of linear-elastic fracture mechanics to wood and fracture parallel to grain, Scient Silv Sinic, 38(6) (2002) 110-115. DOI: 10.1002/nme.2366
[11] Wang, B., Feng, J. C., Qing-Fei, L. I., Study on the effective mechanical properties of foam core sandwich structure reinforced by fiber composite columns, J Harbin Insti Technol, 44(3) (2012) 29-33.
[12] Lee, K. H., Influence of density variation on stress and displacement fields at a propagating mode-iii crack tip in orthotropic functionally graded materials, Trans Korean Society Mechanic Eng., A, 35(2011) 1051-1061.
[13] Jiang, Z., Fei, B., Zhang, D., Application and prospect of digital speckle correlation method on wood science, Eng Sci, 5(11) (2003) 1-7.
[14] Liu, G., Luo, C., Zhang, D., Mechanical performance and failure mechanism of thick-walled composite connecting rods fabricated by resin transfer molding technique, Appl Compos Mater, (2014) 1-14. DOI: 10.1007/s10443-014-9415-2.
[15] Lepov, V., Ivanova, A., Achikasova, V., Modeling of the damage accumulation and fracture: structural-statistical aspects, Key Eng Mater, 345-346 (2007) 809-812.
[16] Yao, G.H., Song, Z.P., Xian-Bin, Y.U., Experimental study on AE characteristics of limestone, Coal Geol Explor, 34(6) (2006) 44-46.
[17] Mba, D., Roberts, T., Taheri, E., Application of acoustic emission technology for detecting the onset and duration of contact in liquid lubricated mechanical seals, Insight, 48(8) (2006) 486-487.
[18] Bai, X., Lee, W.C., Thompson, L.L., Finite element analysis of Moso Bamboo-reinforced southern pine OSB composite beams, Wood Fiber Sci, 31(4) (1999) 403-415.
[19] Huang, S.X., Li-Na, M.A., Shao, Z.P., Relationship between microstructure characteristics and mechanical properties of moso bamboo, J Anhui Agri Univer, 32(2) (2005) 203-206.