J Wood Sci (2015) 61:120–127
DOI 10.1007/s10086-014-1444-9

ORIGINAL ARTICLE

Strength models of bamboo scrimber for compressive properties

Weiwei Shangguan · Yong Zhong · Xinting Xing · Rongjun Zhao · Haiqing Ren

Received: 22 July 2014 / Accepted: 16 October 2014 / Published online: 9 December 2014

Abstract Ten groups of bamboo scrimber samples between 0° (parallel to the grain) and 90° (perpendicular to the grain) were chosen for compression test. The effect of different angles between load and grain on compressive properties of bamboo scrimber was studied. Fold failure, shearing failure and crushing failure were observed at 0–10°, 20–50° and 60–90°, respectively. From 0 to 90°, average ultimate strength and proportional limit strength decreased from 133.4 to 25.7 MPa and 113.9 to 14.9 MPa. The predictive accuracy of the Hankinson formula was higher comparing to the result of GB 50005 formula. The Norris criterion was inclusive for the majority of the testing values, making it secure during application. Furthermore, compressive properties could be predicted using maximum stress theory, which adequately explained the cause of different failure types for longitudinal compression strength, shear strength and transverse compressive strength. The study of strength models now provides a theoretical foundation for the rational use of bamboo scrimber.

Keywords Bamboo scrimber · Compressive properties · Failure modes · Strength model

Introduction

Bamboo resources are rich in China due to their fast-growing and renewable characteristics. Due to their high strength-to-weight ratio and clear texture, bamboos are used widely in vernacular architecture; however, in modern buildings, it presents major challenges for bamboo culms' thin wall and hollow structure as a construction material. To effectively utilize bamboo, it can be processed and reassembled into structure material with high strengths. Bamboo scrimber is an engineering material, where bundles of bamboo fiber are arranged in parallel, with fibers glued to each other using adhesive under a hot press after drying. "Scrimber", originally proposed by Coleman [1, 2], means numerous wood splinters bonded together. Substantial proportion of splinters comprises a matrix of generally aligned splinters, overcoming the anisotropy of natural lumber. The research of bamboo scrimber is mainly carried out in several Asian countries. In 1980s, bamboo scrimber was developed in the laboratory in China. Modulus of rupture (MOR) and modulus of elastic (MOE) of bamboo scrimber were much higher than wood-based panels and ordinary bamboo-based panels [3, 4]. Tensile strength and compression strength parallel to grain of bamboo scrimber (*Neosinocalamus affinis*) are 248.2 and 129.2 MPa, respectively [5], which are much higher than comparative values of lumber. Although good mechanical properties are found in bamboo scrimber, characteristic value and design value are still not available. Strength models, the theoretical basis for ascertaining characteristic value and design value of structural material, provide a mean for this dilemma. Therefore, our research aims to fill in this gap and provide a theoretical basis for more extensive use of bamboo scrimber products.

To establish strength models in spatial stress state, failure criteria need to be explored. Classical failure theories include maximum stress theory, maximum strain theory, maximum shear stress theory and distortion energy theory [6]. Mises [7] proposed plastic value as a basis for distortion energy theory. Von Mises stress is currently used

W. Shangguan · Y. Zhong · X. Xing · R. Zhao · H. Ren (✉)
Research Institute of Wood Industry, Chinese Academy of Forestry, Beijing, China
e-mail: renhq@caf.ac.cn

in Finite Element Method (FEM) simulation software as a criterion. Mechanical properties, which can be influenced by knots and grain, have been simulated by FEM using Von Mises stress [8, 9]. However, Von Mises theory applies only to isotropic materials. Hill [10] extended it for orthotropic materials without distinguishing tensile and compressive strengths. The differences between tensile and compressive strengths are covered in Hoffman criterion [11], which can be seen an extension of Hill criterion. Tsai and Wu [12] developed the Hoffman criterion by establishing stability conditions in relation to strength tensors and magnitudes of the interaction term. There is high consistency between the criterion and experimental results. While the above criteria have been widely used in metal [13], composite material [14] and wood [15], bamboo and bamboo materials have not been studied.

Among numerous failure criterions, the Hankinson formula, Chinese National Standard GB 50005 (Code for design of timber structures) (GB 50005) [16], Norris formula and Maximum stress theory are the most commonly used criteria in China for deriving compressive properties. The purpose of this study is to analyze characteristics of bamboo scrimber compression and compare the four failure criterions by uniaxial compression testing.

Materials and methods

Materials

Neosinocalamus affinis, 3–4 years age, was used as a raw material to produce bamboo scrimber. The untreated bamboos were sawn into bamboo tubes firstly, then fluffed those tubes along the longitudinal fiber direction to interlace bamboo fiber bundles. After that, oriented bamboo fiber bundles were immersed in a PF162510 phenol–formaldehyde resin (Dynea Co., Beijing City, China). The amount of adhesive was controlled to about 15 % of the dry weight of the bamboo scrimber during dipping glue process. To get the target density (1.10 g/cm^3), a temperature of 140 °C and a pressing pressure of 5.0 MPa were carried out during manufacturing. The holding time is 1 min/mm. The nominal dimension of each bamboo scrimber board was 250 cm (Length) × 64 cm (Width) × 3.4 cm (Thickness). The average air-dry density and moisture content were 1.12 ± 0.09 g/cm^3 and 7.42 ± 0.96 %, respectively.

Compression test

Five boards were prepared to process compression specimens. Angles between loading direction and fiber direction ranged from 0 to 90°. 400 specimens in total were tested and analyzed. The samples were separated into 10 groups by different grain angles, each with 40 replicate samples, for different grain angles: 0, 10, 20, 30, 40, 50, 60, 70, 80, and 90°. For each grain angle, eight samples were cut from same board. All samples were selected randomly from the five boards. All specimens were tested at a constant temperature of 20 °C and humidity of 65 %. The sample size was 30 mm (Length) × 20 mm (Width) × 20 mm (Thickness) illustrated in Fig. 1. Compression test was carried out according to Chinese National Standard GB 1935–2009 (Method of testing in compressive strength parallel to grain of wood) [17].

The machine used in this experiment was Instron 5582. The samples were loaded to failure at 1 mm/min. The maximum load was the failure load.

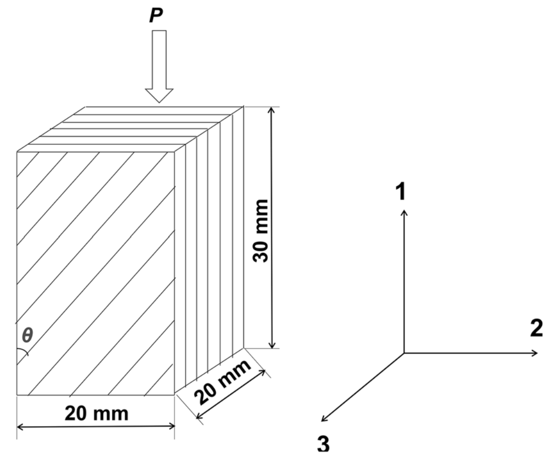

Fig. 1 Specimen size for compressive test at an angle to grain

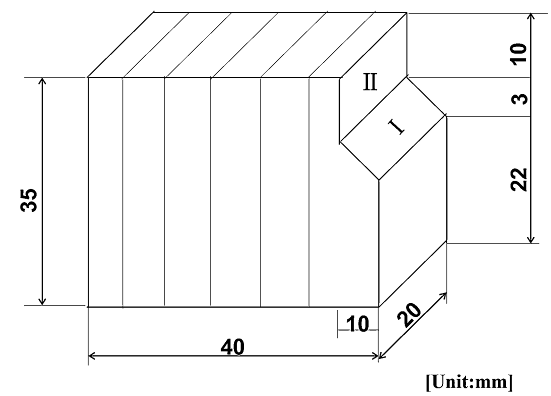

Fig. 2 Shear sample size (mm) parallel to the grain

Shear test

Shear test of bamboo scrimber was performed according to Chinese National Standard GB 1937–2009 (Method of testing in shearing strength parallel to grain of wood) [18].

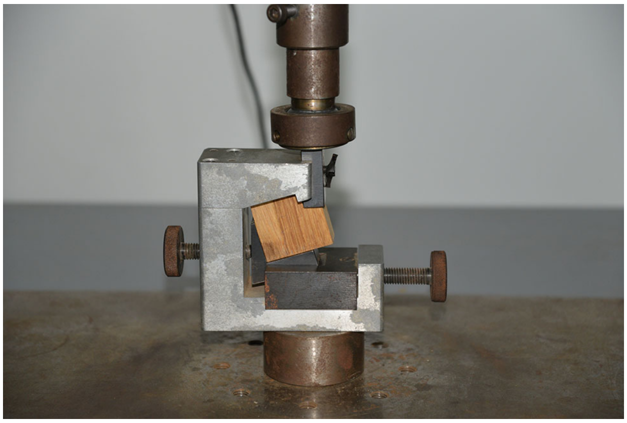

Fig. 3 Shear test setup

This test method is on the base of American Society for Testing and Materials (ASTM) D 143 (Standard test methods for small clear specimens of timber) [19], which is applied on shear strength of wood [20]. Shear strength using this method has been used in structural-laminated veneer lumber [21] and wood [22]. The nominal size of the shear sample is shown in Fig. 2. The plane I (Fig. 2) was applied as pressure-forming shear force relative to the plane II. The angle between the plane I and plane II was 106°40′ ± 20′. NMB AL-50KNB instruments manufactured by TECHNO GRAPH Company in Japan was used in this experiment. The shear test set up is shown in Fig. 3. 40 samples were prepared and tested for shear strength.

Formula of shear strength,

$$\tau = \frac{0.96P_{\max}}{bl} \tag{1}$$

where τ is shear strength parallel to the grain; $P_{\max}$ is the failure load of the specimen; b and l are width and length of the rectangle shear plane (plane I).

Hankinson criterion and GB 50005 criterion

Hankinson [23] first reported compressive strength of spruce at varying angles of grain in 1929,

$$f = \frac{f_1 f_2}{f_1 \sin^2\theta + f_2\cos^2\theta} \tag{2}$$

GB 50005 (Code for design of timber structures) [16] for off-axis compressive properties is widely used in China. The criterion is as follows,

$$f = \frac{f_1}{1 + (\frac{f_1}{f_2} - 1)\frac{\theta - 10^\circ}{80^\circ}\sin\theta} \tag{3}$$

where f is compressive property when the angle is θ. f_1 and f_2 are compressive properties parallel and perpendicular to the grain. θ is the angle between loading direction and grain direction.

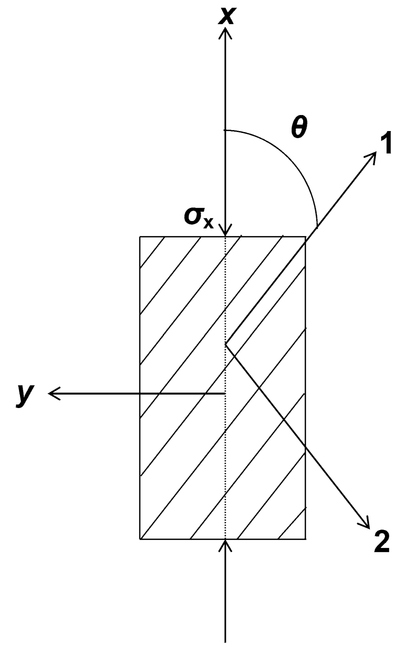

Fig. 4 Off-axis compression

Norris criterion

Norris Criterion [24] was originally proposed in 1956 for the calculation of glue-laminated timber. Now it has been extensively applied for verification of strengths,

$$\left[\left(\frac{\sigma_1}{f_1}\right)^2 + \left(\frac{\sigma_2}{f_2}\right)^2 + \left(\frac{\tau_{12}}{S}\right)^2\right]^{\frac{1}{2}} \le 1.0 \tag{4}$$

where σ_1 and σ_2 are compressive stresses parallel and perpendicular to the grain. τ_{12} stands for shear stress. f_1 and f_2 are compression strengths of wood parallel and perpendicular to the grain. S means shear strength.

In the case of off-axis compression, stresses must be transformed using a transformation equation for the principal directions (1 and 2 directions) of materials. 1 and 2 are assumed as longitudinal directions parallel and perpendicular to grain, respectively, in Fig. 4. Compressive stress σ_x is decomposed to σ_1 parallel to grain, σ_2 perpendicular to grain and shear stress τ_{12}.

Norris criterion is expressed in Eq. (5),

$$\left[\left(\frac{\sigma_x\cos^2\theta}{f_1}\right)^2 + \left(\frac{\sigma_x\sin^2\theta}{f_2}\right)^2 + \left(\frac{\sigma_x\sin\theta\cos\theta}{S}\right)^2\right]^{\frac{1}{2}} \le 1.0 \tag{5}$$

Maximum stress theory

Maximum stress theory [25] is the basic theory of orthotropic-laminated plates. This theory requires that stresses along principal axes must be less than the strength of this direction. Failure occurs when any of the stress components along the principle axes exceeds the corresponding strength in that direction. It is the most widely used in the design and analysis of composite material due to its simplicity.

$$\begin{aligned} &\sigma_1 < |X_c| \\ &\sigma_2 < |Y_c| \\ &|\tau_{12}| < S \end{aligned} \quad (6)$$

where X_c, Y_c and S are longitudinal compressive strength, transverse compressive strength and shear strength of bamboo scrimber.

For the case shown in Fig. 4, Maximum stress theory is expressed in Eq. (7),

$$\begin{aligned} &\sigma_x < X/\cos^2\theta \\ &\sigma_x < Y/\sin^2\theta \\ &\sigma_x < S/(\sin\theta\cos\theta) \end{aligned} \quad (7)$$

σ_x takes minimum of the three inequalities as the material maximum failure stress.

Results and discussion

Failure types

In the compression test, the load of bamboo scrimber declined sharply when pressure reached a maximum. Then deformation of the sample grew rapidly. Different failure types at various grain angles were found in the testing process.

In Fig. 5, specimens of 0–10° grain angles displayed wrinkled failure along the grain direction. Adhesive layers cracked severely because of inter-laminar stresses, which existed on the surface of fiber bundle. Inter-laminar stress reached a maximum at the interface. Samples of 0–10° delaminated at the free boundary as shown in Fig. 5a. For specimens of 20–50°, shear failure cracking was observed along the grain direction. Bonding strength among fibers is much lower than the single fiber strength [26]. This led to weak areas at bonded regions when subjected to shear force. Samples of 60–90° were crushed horizontally along grain direction as shown in Fig. 5c. All failure types of bamboo scrimber cracked along the grain direction. This illustrates that bonding among bamboo fibers is primary weakness of mechanical properties. Failure types in this experiment are consistent with pine wood investigated by Galicki and Czech [27].

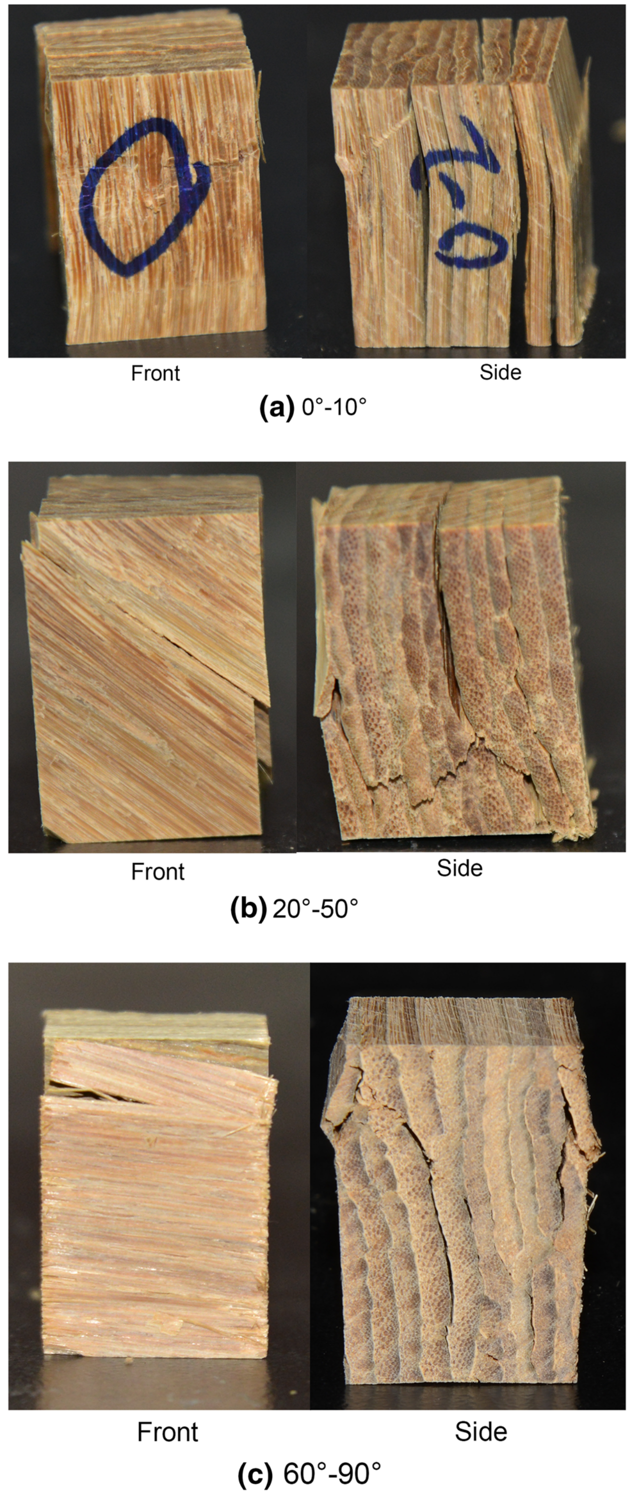

Fig. 5 Failure types of bamboo scrimber at varying angles of grain. **a** 0–10°, **b** 20–50°, **c** 60–90°

Compression performances of bamboo scrimber

Figure 6 shows that the initial stages of load curves are linear, which indicates elastic deformation of compression. As load increased, the specimens displayed plastic deformation. The yield point of samples for θ = 0–10° was not obvious in Fig. 6a. Load decreased significantly during plastic deformation after reaching a maximum. Peak load

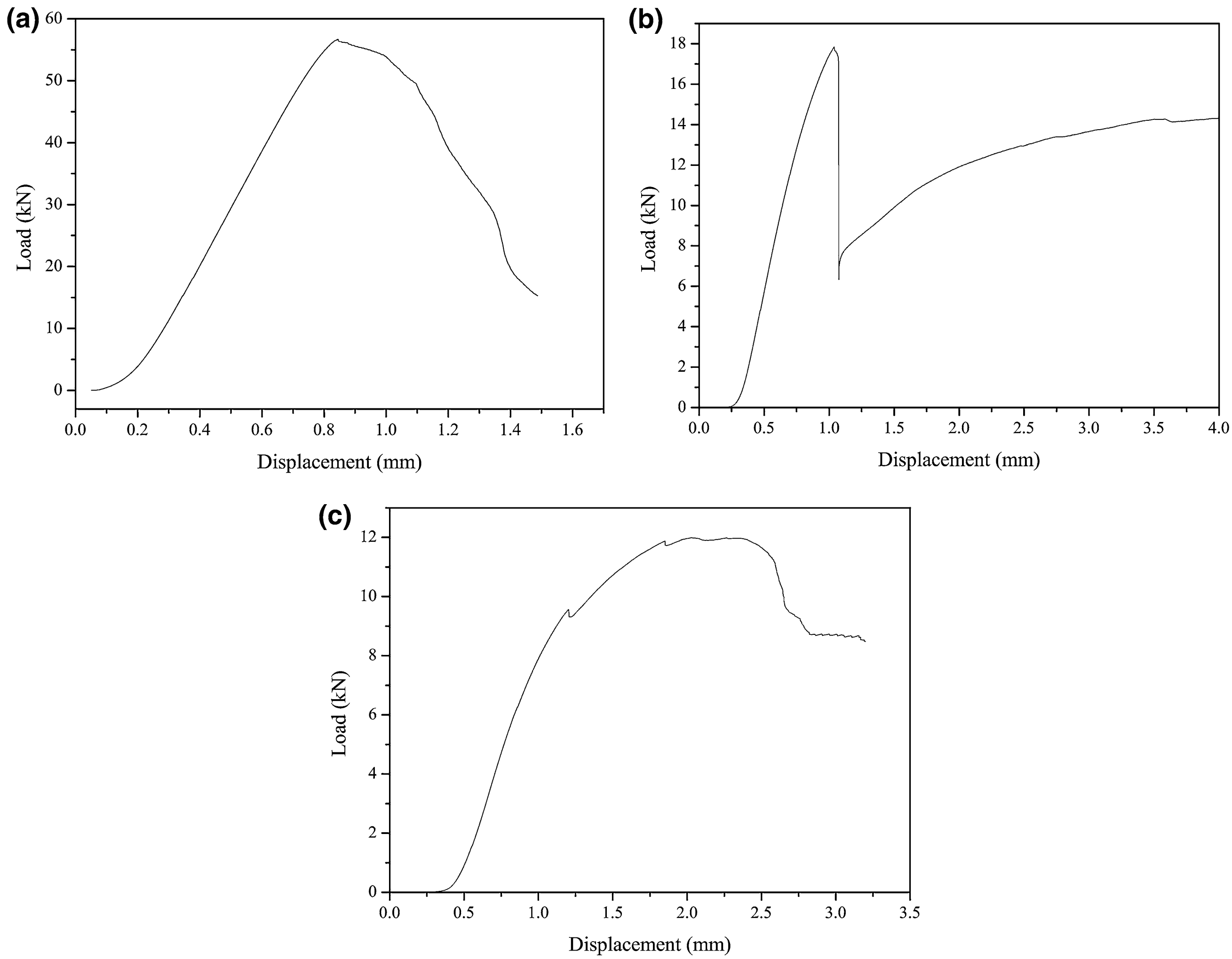

Fig. 6 Load-displacement curves at varying angles of grain. **a** 0–10°, **b** 20–50°, **c** 60–90°

at 10° was lower than it at 0° due to shear stress, which is absent for 0° specimen. Apparently yield appeared obviously between 20 and 50° specimens in Fig. 6b. After reaching a maximum, the load declined sharply, and then rose slowly during the most serious stage of deformation. This could be the result of the two planes, which were destroyed by shear stress, contacted with each other as displacement increases. For samples of 60–90°, fibers horizontally arranged were compacted, so the load platform could remain. A Distinct plateau region in Fig. 6c is also found in spruce stress–strain curves [28]. This illustrates the plastic yielding and collapsing of cells [29, 30].

Table 1 shows ANOVA analysis of compression performance. Letters of A-G indicated the significant differences among those mechanical properties. Same letters mean no significant differences among corresponding properties, while different letter means significant differences among them. Table 1 shows that significant differences of ultimate compression strength exist in samples of 0–40°. The letters of F for $\theta = 60–70°$ and G for $\theta = 80–90°$ illustrate no significant differences exist in samples of 60–70° and 80–90°. For proportional limit strength, letters changed from A to F while grain direction varied from 0 to 50°, showing significant differences existed among these samples. And no significant differences existed in samples of 50–60° and 70–90°. From ANOVA analysis (Analysis of Variance), compressive properties changed greatly at small angles and slightly changed at large grain angles. Wrinkled failure and shear failure occurring in samples of 0–50° had a great impact on compressive properties. However, horizontal failure occurring in samples of 60–90° had less impact.

Hankinson criterion, GB 50005 criterion and Norris criterion

Substituting mechanical properties of 0 and 90° into Eq. (2) and (3), we obtained simulation curves by

Table 1 One-way ANOVA of compression performances for bamboo scrimber (Duncan's multiple range test)

Grain direction	Ultimate compression strength	Proportional limit strength
0°	A	A
10°	B	B
20°	C	C
30°	D	D
40°	E	E
50°	E	F
60°	F	F
70°	F	G
80°	G	G
90°	G	G
F value	1347.30	1170.51
$p > F$	<0.01	<0.01

Significant difference exists in the samples of compressive properties when the letters are different. Grain directions followed by the same letter are not significantly different at the 0.01 probability level

Hankinson criterion and GB 50005 criterion. Ultimate strengths at 0 and 90° are substituted in Eq. (5). The average shear strength tested in this experiment was 24.0 (±2.4) MPa. The curve by Norris criterion can be fitted. Fitted curves of Norris criterion, Hankinson criterion and GB 50005 criterion are shown in Fig. 7.

In Fig. 7, measured values of compressive mechanical properties of bamboo scrimber reached a maximum at 0° along the grain direction. Average ultimate strength and proportional limit strength decreased with increasing grain angle from 133.4 to 25.7 MPa and 113.9 to 14.9 MPa, respectively. Spruce compressive strength follows the same trend from values around 49 MPa at loading parallel to the tracheids to values around 3 MPa when the loading direction is parallel to the radial orientation [26]. The deviations of ultimate strength and proportional limit strength may be due to microcracks in the samples. Compressive properties for 0–50° declined at a larger rate than 50–90°, indicating that change of small grain angle can cause great change of mechanical properties when grains are nearly parallel to the load direction. Tensile strength of laminated veneer lumber displays the same trend, showing rapidly decreases at an orientation between 0 and 15° [31]. This phenomenon is consistent with ANOVA analysis, which shows significant differences among compressive properties of samples of 0–50° (Table 1) and little among those of samples of 50–90°.

Hankinson, GB 50005 and Norris criterions are able to predict the tendency of compression performances for bamboo scrimber. Predicted values of GB 50005 were larger than tested compressive strength at 0–60° and larger than tested proportional limit strength at 0–40°. This suggests that it is inappropriate to use GB 50005 criterion to predict compressive properties of bamboo scrimber at small grain angles. Predicted values of Hankinson criterion were close to test values for both compressive strength and proportional limit strength. Predicted Norris values were found to be at the lower limit of testing values of compressive strength. However, curves of Norris and Hankinson criteria for proportional limit strength overlap. Both Hankinson criterion and Norris criterion can be used to predict proportional limit strength of bamboo scrimber at various grain angles. It can be concluded that Hankinson formula predicts compressive properties with the highest accuracy, while the Norris formula ensures the security of projects. However, GB 50005 is not recommended for use due to its inaccuracy and lack of security.

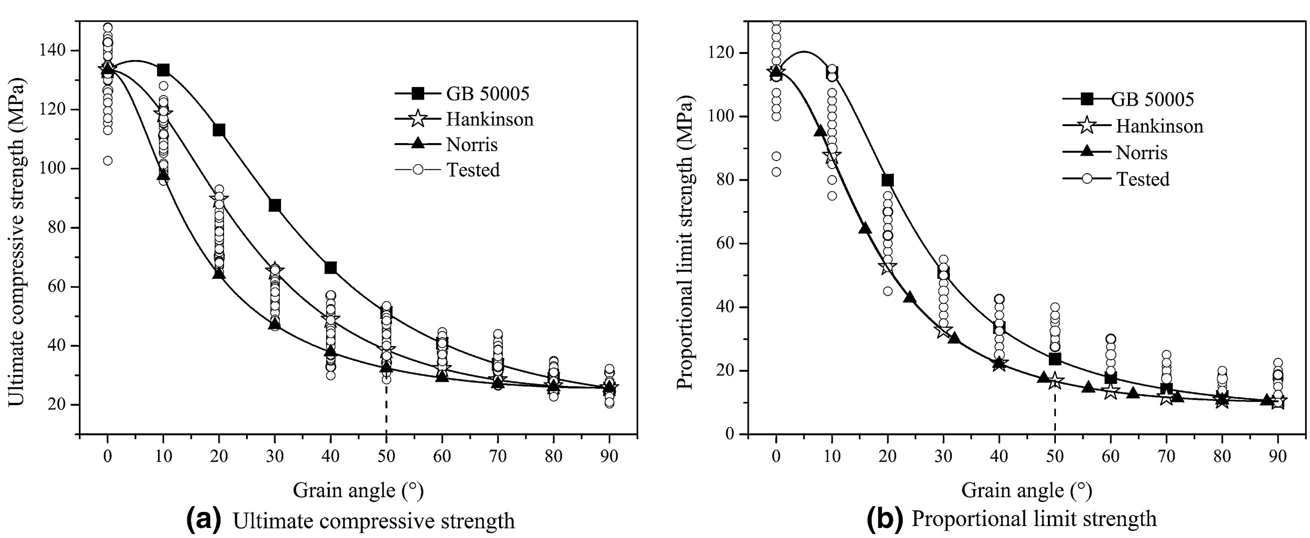

Fig. 7 Fitted curves of Norris, Hankinson and GB 50005 criterions. **a** Ultimate compressive strength, **b** Proportional limit strength

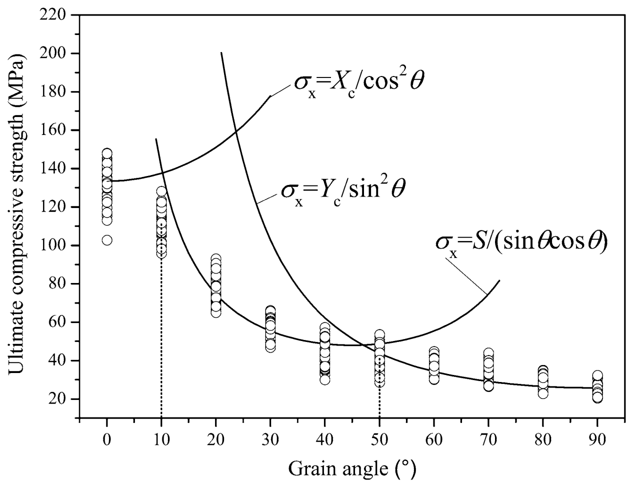

Fig. 8 Failure criteria for tested bamboo scrimber specimens in the maximum stress theory

Maximum stress theory

Substituting compression strengths and shear strength into Eq. (7), strength curves of maximum stress theory are shown in Fig. 8.

Maximum stress theory can predict compressive strength of bamboo scrimber accurately. The lowest curves at different angles are the strength control curves in Fig. 8. The curve of $\sigma_x = S/(\sin\theta\cos\theta)$ intersects with curves of $\sigma_x = X_c/\cos^2\theta$ and $\sigma_x = S/\sin^2\theta$. The intersectional points are near 10 and 50° test samples, respectively. The three strength control curves of samples for θ = 0–10°, 10–50°, and 50–90° are compressive strength parallel to the grain, shear strength and compressive strength perpendicular to the grain, respectively. The three intervals for strength control curves are consistent with demarcation points of failure types observed in the experiment, which display longitudinal wrinkled failure (samples of 0–10°), shear failure (samples of 10–50°) and horizontal failure (samples of 50–90°) in the experiment. It may be explained that compressive strength parallel to the grain results in longitudinal wrinkled failure type, shear strength leads to shear failure, and compressive strength perpendicular to the grain causes horizontal failure. Measured values and strength control curves fitting well illustrates that maximum stress theory is suitable for predicting compressive strength of bamboo scrimber. In LVL tensile experiment, the Maximum stress theory shows some difference compared to the actual data under 45°. Oh [31] considers that this is due to inaccuracy of shear stress.

Conclusions

1. A uniaxial compression test of bamboo scrimber showed wrinkled failure at 0–10°, shear failure at 20–50° and horizontal failure which has little effect on compressive properties at 60–90°.
2. Norris values are the lower limit of testing values, Hankinson values are close to tested values, and predictive values of GB 50005 are higher than tested values.
3. Maximum stress theory can predict compressive strength. It explains the division of failure types. The results verified accuracy of the criterions for predicting compressive properties of bamboo scrimber. But more information is needed for full-scale samples of bamboo scrimber.

Acknowledgments We gratefully acknowledge the financial support from "the National Science and Technology Pillar Program during the 12th Five-year Plan Period: Research and Demonstration of manufacturing technologies for green bamboo building materials (2012BAD23B01)."

References

1. Coleman JD, Hills S (1980) Reconsolidated wood product. US Patent 4232067
2. Coleman JD (1981) A "reconsolidated" wood for structural purposes. Division of Chem tech CSIRO, Australia, pp 1–10
3. Zhang FW, Yu WJ (2008) Research status and prospect of wood/bamboo reconstituted structural material. China For Prod Ind 35:7–12
4. Yu WJ (2011) Development of bamboo-fiber based composites. China Wood Ind 25:6–8
5. Zhang JZ, Ren HQ, Zhong Y, Zhao RJ (2012) Analysis of compressive and tensile mechanical properties of bamboo scrimber. J Nanjing For Univ 36:107–111
6. Sun XF, Fang XS (2011) Mechanics of materials. Higher Education Press, Beijing, pp 234–237
7. Mises R (1913) Mechanics of solid bodies in the plastically-deformable state (in German). Göttin Nachr Math Phys 1:582–592
8. Bano V, Arriaga F, Soilán A, Guaita M (2011) Prediction of bending load capacity of timber beams using a finite element method simulation of knots and grain deviation. Biosyst Eng 109:241–249
9. Guindos P, Ortiz J (2013) The utility of low-cost photogrammetry for stiffness analysis and finite-element validation of wood with knots in bending. Biosyst Eng 114:86–96
10. Hill R (1948) A theory of the yielding and plastic flow of anisotropic metals. Proc Royal Soc A 193:281–297
11. Hoffman O (1967) The brittle strength of orthotropic materials. J Compos Mater 1:200–206
12. Tsai SW, Wu EM (1971) A general theory of strength for anisotropic materials. J Compos Mater 5:58–80
13. Benoit RB, Cazacu O (2014) Role of the plastic flow of the matrix on yielding and void evolution of porous solids: comparison between the theoretical response of porous solids with Tresca and von Mises matrices. Mech Res Commun 56:69–75
14. Kolakowski Z (2003) On some aspects of the modified TSAI-WU criterion in thin-walled composite structure. Thin-Walled Structures 41:357–374
15. Mascia NT, Simoni RA (2013) Analysis of failure criteria applied to wood. Eng Fail Anal 35:703–712

16. Chinese National Standard GB 50005-2003 (2003) Code for design of timber structures (in China). Ministry of Construction, Beijing, p 16
17. Chinese National Standard GB 1935–2009 (2009) Method of testing in compressive strength parallel to grain of wood. Standardization Administration of China, Beijing
18. Chinese National Standard GB 1937–2009 (2009) Method of testing in shearing strength parallel to grain of wood. Standardization Administration of China, Beijing
19. ASTM D 143–2009 (2009) Standard test methods for small clear specimens of timer. American Society for Testing and Materials, West Conshohocken
20. Gupta R, Sinha A (2011) Effect of grain angle on shear strength of Douglas-fir wood. Holzforschung 66:655–658
21. Zhong Y, Xing XT, Ren HQ, Zhang R (2014) Properties of structural laminated veneer lumber in compression at an angle to grain. J Build Mat 17:115–119
22. Qin DC, Fu F, Jiang ZH (2004) A new test method for shear strength parallel to wood grain. China Wood Ind 18:10–13
23. Hankinson RL (1921) Investigation of crushing strength of spruce at varying angles of grain. Air Serv Inf Circ 259:1–15
24. Norris CB, McKinnon PF (1956) Compression, tension and shear tests on yellow-poplar plywood panels of sizes that do not buckle with tests made at various angles to the face grain. For Prod Lab Rep 1328:1–50
25. Jenkin CF (1920) Report on materials of construction used in aircraft and aircraft engines. His Majesty Stationary Office, London
26. Yu Y, Jiang ZH, Fei BH, Wang G, Wang HK (2011) An improved microtensile technique for mechanical characterization of short plant fibers: a case study on bamboo fibers. J Mater Sci 46:739–746
27. Galicki J, Czech M (2013) A new approach to formulate the general strength theories for anisotropic discontinuous materials. Part A: the experimental base for a new approach to formulate the general strength theories for anisotropic materials on the basis of wood. Appl Math Model 37:815–827
28. Alexander R, Stefanie EST (2001) Compressive behaviour of softwood under uniaxial loading at different orientations to the grain. Mech Mater 33:705–715
29. Maiti SK, Gibson LJ, Ashby MF (1984) Deformation and energy absorption diagrams for cellular materials. Acta Metall 32:1963–1975
30. Gibson LJ, Ashby MF (1997) Cellular Solids. Cambridge University Press, Cambridge, pp 394–403
31. Oh SC (2011) Applying failure criteria to the strength evaluation of 3-ply laminated veneer lumber according to grain direction by uniaxial tension test. Constr Build Mater 25:1480–1484