Research Progress on Dynamic Testing Methods of Wood Shear Modulus: A Review

Zheng Wang,[a] Dong Zhang,[a] Zhiheng Wang,[b,]* Xingyu Liang,[a] Xiaojun Yang,[a] and Jun Wang [c]

Wood is a non-homogeneous and orthotropic natural polymer material. It is important to test the wood shear modulus and elastic constants accurately and reliably using dynamic methods. Based on the introduction of the advantages of six common methods for dynamic testing of wood shear modulus, such as free plate torsional mode method, free bar torsional vibration method, and Timoshenko beam iterative method, issues associated with the applicability and accuracy of these methods are also pointed out. Recent methods, such as the free square plate torsional mode method and the square plate static torsional strain method, that were developed to dynamically test the shear modulus of wood and wood composite materials, are presented as effective ways to tackle these issues. These new approaches are expected to provide beneficial technical support for using small specimens, overcoming the size effect of specimens, simplifying the testing procedures, improving the test accuracy, and expanding the application range in the dynamic testing of wood shear modulus. These approaches have practical significance in promoting the industrialization and development of structural engineering, furniture and interior decoration, transportation, military, and musical instrument industries.

DOI: 10.15376/biores.18.1.Wang

Keywords: Wood; Wood composite materials; Shear modulus; Dynamic test; Applicability; Test accuracy; Research progress

*Contact information: a: College of Materials Science and Engineering, Nanjing Forestry University, Nanjing, 210037, China; b: Sonny Astani Department of Civil and Environmental Engineering, University of Southern California, Los Angeles, CA, USA; c: College of Information Science and Technology, Nanjing Forestry University, Nanjing, 210037, China; * Corresponding author: zhihengw@usc.edu*

INTRODUCTION

Although a variety of new materials have been developed, wood and wood composite materials, such as plywood, fiberboard, and particleboard, have been widely used and always have maintained an important role in structural engineering, building decoration engineering, furniture, and transportation industries because of their convenient processing and unique excellent characteristics. However, as a non-homogeneous and orthotropic natural polymer material, wood is different from other materials in many properties (Yin 1996). The elastic modulus (E), shear modulus (G), and Poisson's ratio (μ) that characterize elastic constants of materials are the fundamental physical parameters of materials. For wood, there are nine independent elastic constants, which are the E, G, and μ in the three main directions, respectively. It is important to use a convenient and accurate dynamic testing method to study these main-direction elastic constants of wood (Timoshenko 1965; Zhang 1992). There has been progress in testing the E, G, and μ of wood using dynamic vibration methods of free board and cantilever board (Gong 1995; JIS A1127 (2001); Wang *et al.* 2015a, 2017a, 2018; Zhang *et al.* 2021; He *et al.* 2022). Among these, the methods for testing elastic modulus are relatively mature (Ilic 2003; Wang and Wang 2004; Wang 2007; Zhou *et al.* 2007; Turk *et al.* 2008; Wang *et al.* 2012, 2013, 2014a,b, 2015b; Li *et al.* 2021a,b,c; Li *et al.* 2022). However, there are still many challenges in the applicability and accuracy associated with the dynamic testing of wood shear modulus (Hu *et al.* 2001; Thomas 2002; Zhou *et al.* 2007; Wang *et al.* 2014c, 2016a,b, 2017b, 2019a,b,c; Gao *et al.* 2016; Huang *et al.* 2021). Because of the complex nature of wood and manufacturing procedures of wood composites, probabilistic methods should be integrated to study mechanical properties of these materials to provide quantitative estimates of various sources of uncertainty (Peng *et al.* 2018; Wang and Ghanem 2019, 2021, 2022). In this paper, the advantages and disadvantages of six commonly used methods for dynamic testing of wood shear modulus are evaluated, such as the free board torsional vibration method, the free bar torsional vibration method, and the Timoshenko beam iterative method. Moreover, recently developed methods are presented, including the free square board torsional mode method and the static square board torsional strain method, which provide effective means to tackle the aforementioned issues. These new methods have strong theoretical basis and application value to promote the development of testing techniques for mechanical properties of wood and wood composite materials.

Review of Common Methods for Dynamic Testing of Wood Shear Modulus

At present, the methods for dynamic testing of wood shear modulus include the free board torsional vibration method (Wang *et al.* 2019d), the free bar torsional vibration method (Nakao and Okano 1987), the free square board torsional vibration method (JIS A1127-(2001)), the cantilever bar torsional vibration method, the cantilever board torsional mode method (Wang *et al.* 2016a), and the Timoshenko beam iterative method. Comments on the basis, applicability, and test accuracy of the foregoing six test methods are as follows:

(1) *Free board torsional vibration method*: The free board torsional vibration method is used to test the longitudinal (*i.e.*, along grain) and tangential shear modulus (G_{LT}), longitudinal and radial shear modulus (G_{LR}), and transverse shear modulus (G_{RT}) of isotropic materials and wood. Based on the first-order torsional vibration of the board, the relationship between the first-order torsional frequency and the shear modulus of the free board is obtained using the energy method. The mode shape coefficient introduced in this relationship is a new concept that is related to the type of material and the size of the specimen. Moreover, the correctness of this method in testing shear modulus of wood and isotropic materials has been verified by the simulation calculation of the shear modulus, the static square board torsional strain method, the asymmetric four-point bending beam method, and the free bar torsional mode shape method. In contrast, the disadvantage is that the free board torsional mode shape method must satisfy the requirement that the length-to-width ratio of the wood free board specimen is $10 \geqslant l/b \geqslant 3$, that is, this method is limited by the size of the board.

(2) *Free bar torsional vibration method*: When using the free bar torsional vibration method to test the shear modulus of wood and wood materials, according to the tests on different specimens from various tree species, the difference between its test result and that by the free board torsional mode shape method is approximately 7%. However, for shear

modulus testing, from the perspective of test accuracy, this method still has a limit on the length-to-width ratio of the specimen.

(3) *Free square board torsional vibration method*: The shear modulus of wood and wood materials can be dynamically measured by the free square board torsional vibration method. Through the classical square board torsional vibration method, the first-order torsional frequency of the square board is first measured, and then the shear modulus is calculated based on the first-order torsional frequency. It is noted that the equation for calculating the shear modulus adopts a fixed coefficient of 0.9, which is independent of the material type and the width-to-thickness ratio of the square board, which inevitably produces errors.

(4) *Cantilever bar torsional vibration method:* The cantilever bar torsional vibration method is used to test the shear modulus of wood and wood composite materials. In this method, a torsional vibration equation of a cantilever bar with rectangular section is introduced according to the energy method. The shear modulus of wood and wood composite board is calculated from the measured first-order torsional frequency of the cantilever bar. This method does not need to include the tensile (or compression) strain energy when using the relationship between the first-order torsional frequency and the shear modulus of the cantilever bar according to the energy method. From the concept of mechanics, the torsion of the cantilever bar is a restrained torsion under which there must be tensile (or compression) deformation in the cantilever bar. In particular, for the cantilever board with the length-to-width ratio of less than three, the tensile (or compression) strain energy in the cantilever bar must be taken into account and cannot be ignored. However, the tensile (or compression) strain energy is not included in the cantilever bar torsional vibration method. Therefore, the theoretical basis of this method is insufficient, the test results are greatly affected by the length-to-width ratio of the test specimen, and thus the test accuracy is difficult to guarantee.

(5) *Cantilever board torsional mode method*: The shear modulus of wood can be dynamically measured by the cantilever board torsional mode method. This method presents the principle and technique of testing the shear modulus of orthotropic wood and isotropic materials based on the torsional mode of the cantilever board, and is not only applicable to testing the three main shear modulus G_{LT}, G_{LR}, and G_{RT} of wood but also to the shear modulus of isotropic materials. When applying the energy method, the strain energy takes into account not only the torsional strain energy, but also the tensile (or compressive) strain energy, which is the contribution of this test method, so that the tested shear modulus has high accuracy and the test value is independent of the length-to-width ratio of the specimen. This method has been verified by the results from various tree species. The limitation of the cantilever board torsional mode method is that the length-to-width and the width-to-thickness ratios of the wood cantilever board test specimen are required to be $5 \geqslant l/b \geq 2$ and $13.67 \geqslant b/h \geq 6.83$, respectively.

(6) *Free beam iterative method*: The free beam iterative calculation method is used to test the elastic modulus and shear modulus of materials. This method is based on the Timoshenko beam theory, that is, the influence of shear force and rotation effect of the beam on its bending frequency is considered under lateral vibration of the beam. When using this method, the first- and second-order bending frequencies of the free beam are first tested, then the elastic and shear modulus of the material are calculated simultaneously within an iterative procedure. The free beam iterative method also has the limitation on the size of the test specimen and can even lead to divergent iterative results.

Table 1. Review of Common Methods for Dynamic Testing of Wood Shear Modulus

No.	Name	Advantage	Improveable
1	Free board torsional vibration method	This method starts from the first-order torsional vibration mode of the board, derives the relationship between the test shear modulus by using the energy method, and puts forward a new concept of mode shape coefficient, whose value is related to the type of material and the size of the specimen. The effectiveness of this method has been verified by static tests.	This method must satisfy the requirement that the length-to-width ratio of the wood free board specimen is 10≥ *l/b*≥3.
2	Free bar torsional vibration method	This method can dynamically test the shear modulus of wood and wood materials, and the difference between the test results and those of the free board torsional mode shape method is approximately 7%.	Considering the test accuracy, this method has a limit on the length-to-width ratio of the specimen.
3	Free square board torsional vibration method	This method can dynamically measure the shear modulus of plywood and isotropic materials. The first-order torsional frequency of the square board is first measured, and then the shear modulus is calculated based on the first-order torsional frequency.	Considering the test accuracy, this method is not suitable for testing wood shear modulus.
4	Cantilever bar torsional vibration method	This method uses a torsional vibration equation of a cantilever bar with rectangular section from the energy method and calculates the shear modulus *G* of wood and wood composite board by measuring the first-order torsional frequency of the cantilever bar.	This method does not include the tensile (or compressive) strain energy, and lacks theoretical basis. The test results are greatly affected by the length-to-width ratio of the test specimen, and the test accuracy is difficult to guarantee.
5	Cantilever board torsional mode method	The theoretical basis of this method is sufficient. When applying the energy method, the strain energy takes into account not only the torsional strain energy, but also the tensile (or compressive) strain energy, so that the tested shear modulus has high accuracy and the test value is independent of the length-to-width ratio of the specimen. It is not only applicable to testing the three main shear modulus G_{LT}, G_{LR}, and G_{RT} of wood but also to the shear modulus of isotropic materials.	This method requires that the length-to-width and the width-to-thickness ratios of the wood cantilever board test specimen are 5≥ *l/b* ≥ 2 and13.67≥*b/h*≥ 6.83, respectively, that is, the cantilever board is limited by the length-to-width and the width-to-thickness ratios.
6	Free beam iterative method	This method is based on the Timoshenko beam theory, the first-order and second-order bending frequencies of the free beam are first tested, then the elastic and shear modulus of the material are calculated simultaneously within an iterative procedure.	This method is also limited by the size of the specimen and material type, and even iterative divergence, the shear modulus cannot be tested.

Main Approaches to Improve the Applicability and Test Accuracy of Dynamic Test Methods for Wood Shear Modulus

Shear modulus is an important elastic constant of materials. The testing of wood shear modulus should not be limited by the size of the specimen. A test method that is limited by the specimen size can provide results, but its accuracy is difficult to guarantee, which makes it unreliable in practice. The application and testing accuracy of the dynamic testing of shear modulus of wood and wood composite materials can be improved by the recently developed methods: the free square board torsional mode method, the square board static torsional strain method (Wang *et al.* 2019e), and the cantilever square board torsional vibration method, which are all tailored to the challenges presented in the foregoing section, particularly in terms of the test method, specimen size, and accuracy. These new methods leverage principles from material mechanics, elastic mechanics, and mechanical dynamics, and integrate the theoretical methods and testing techniques from wood grain structure and wood mechanics in wood science. Their main characteristics are as follows:

(1) *Free square board torsional mode method*: In determining the relationship between the free square plate's first-order torsional frequency and its shear modulus, the free square plate torsional mode method provides the theoretical underpinnings for the dynamic measurement of the shear modulus of wood and wood composite materials. The applicable range of the width-to-thickness ratio of the square board is extended to 7 to 30. Moreover, a particular innovation is in the reduction of the width-to-thickness ratio of the square board to the range from 10 to 15, while the test accuracy of the shear modulus is still guaranteed. For example, the static methods for testing wood shear modulus using square plates as test specimen include: the ASTM D3044-16 (2016) standard method, the National Physical Laboratory (NPL) method, the modified NPL (MNPL) method, and Lee's method (Yoshihara and Sawamura 2006; Yoshihara 2009), of which the common feature is that the shear modulus is calculated by measuring the deflection at the loading point using sufficiently thin square board specimens. Therein the width-to-thickness ratio of square plate specified in ASTM D3044-16 (2016) is from 25 to 40; the NPL method and the Lee's method adopt the width-to-thickness ratio as no less than 35, which was proposed Sims *et al.* (1994).

(2) *Square plate static torsional strain method*: The square plate static torsional strain technique determines the relationship between the linear strain of the square plate's two central points along the direction of 45° and its shear modulus to tackle the impact of the loading location on the test value of the shear modulus. This approach relaxes the need for square plate’s width-to-thickness ratio while improving the test accuracy by proposing a width-to-thickness ratio of 10 to measure shear modulus. Whereas the influence of loading location on the tested shear modulus value cannot be addressed by the standard static torsional deflection method.

(3) *Cantilever* s*quare plate static torsional strain method*: The cantilever square plate torsional vibration method for dynamic testing of wood and wood composite shear modulus can quantitatively address the difference between the shear modulus along and across grain of the specimen, such as the numerical difference between G_{LT} and G_{TL}. At present, the dynamic test of wood shear modulus is limited to the three main-direction shear modulus G_{LT}, G_{LR}, and G_{RT}. Actually, the specimens cut from the longitudinal and transverse directions associated with each main direction also involve other three shear modulus: G_{TL}, G_{RL}, and G_{TR}, but research on this topic has not been published yet, to the knowledge of the authors. The cantilever square plate torsional vibration method can quantitatively measure the difference in shear modulus between specimens cut

longitudinally and transversely, and eliminate the size effect of the tested shear modulus, because the longitudinal and transverse dimensions of the cantilever square plate are equal, and the change from directions LT, LR, or RT to directions TL, RL, or TR is achieved by changing the clamping edge. Therefore, using this method to test wood shear modulus can comprehensively reflect the orthotropic characteristics of wood.

CONCLUSIONS

1. The commonly used methods for dynamic testing of wood shear modulus have been reviewed in this article. Emphasis has been placed on existing challenges, as well as the main approaches to improve the applicability and test accuracy. The methods considered included the free square plate torsional mode method, the square board static torsional strain method, and the cantilever square plate torsional vibration method.
2. Common features of the advocated approaches include: (1) A small specimen is used in the dynamic test, which is consistent with the anisotropic and non-homogeneous characteristics of wood and wood composite board; (2) the size effect of the test specimen is eased; (3) the test method is simplified, fast, and convenient; and (4) the test accuracy is improved. These new testing methods can have practical significance in promoting the industrialization and development of structural engineering, furniture and interior decoration, transportation, military, and musical instrument industries.

REFERENCES CITED

ASTM D3044-16 (2016). "Standard test method for shear modulus of wood-based structural panels," ASTM International, PA, USA.

Gao, Z., Wang, Z., Zhang, X., Xu, L., and Liu, B. (2016). "The frequency method for measurement and evaluation of shear modulus of *Picea sitchensis* soundboard," *China Forest Products Industry* 43(02), 23-26. DOI: 10.19531/j.issn1001-5299.2016.02.010

Gong, M. (1995). "A study of wood elastic parameters parallel to grain in compression test by using resistance strain gages," *Scientia Silvae Sinicae* 31(2), 189-191.

He, Y., Zhang, Y., Huang, Y., Zhou, Y., and Wang, Z. (2022). "Analysis of the influence of accelerometer quality and installation position on the test value of wood material constant," *China Forest Products Industry* 59(01), 41-48. DOI: 10.19531/j.issn1001-5299.202201007

Hu, Y., Wang, F., Liu, Y., and Nakao, T. (2001). "Nondestructive testing of the dynamic shear modulus of elasticity for particleboard," *Journal of Northeast Forestry University* 29(2), 17-20. DOI: 10.3969/j.issn.1000-5382.2001.02.005

Huang, Y., Chen, S., Dauletbek, A., Yang, X., Wang, J., Sun, Xie, W., and Wang, Z. (2021). "Dynamic testing of the elastic modulus and shear modulus of full-scale laminated veneer lumber," *BioResources* 16(4), 8273-8288. DOI: 10.15376/BIORES.16.4.8273-8288

Ilic, J. (2003). "Dynamic MOE of 55 species using small wood beams," *Holz als Roh-und Werkstoff* 61(3), 167–172. DOI: 10.1007/s00107-003-0367-8

JIS A1127 (2001). "Methods of test for dynamic modulus of elasticity, rigidity and Poisson's ratio of concrete by resonance vibration," Concrete Engineering Association of Japan, Tokyo, Japan.

Li, H., Wang, B. J., Wang, L., Wei, P., Wei, Y., and Wang, P. (2021a). "Characterizing engineering performance of bamboo-wood composite cross-laminated timber made from bamboo mat-curtain panel and hem-fir lumber," *Composite Structures* 266, article ID 113785. DOI: 10.1016/j.compstruct.2021.113785

Li, H., Wang, L., Wang, B. J., Wei, P., and Du, G. (2021b). "Preliminary evaluation of a density-based lumber grading method for hem-fir CLT manufacturing," *European Journal of Wood and Wood Products* 79(4), 967-975. DOI: 10.1007/s00107-020-01653-3

Li, H., Wang, L. B., Wei, Y., Wang, B. J., and Jin, H. (2021c). "Bending and shear performance of cross-laminated timber and glued-laminated timber beams: A comparative investigation," *Journal of Building Engineering* 45, article ID 103477. DOI: 10.1016/j.jobe.2021.103477

Li, H., Wang, L. B., Wei, Y., and Wang, B. J. (2022). "Off-axis compressive behavior of cross-laminated bamboo and timber wall elements," *Structures* 35, 452-468.

Nakao, T., and Okano, T. (1987). "Evaluation of modulus of rigidity by dynamic plate shear testing," *Wood and Fiber Science* 19(4), 332-338.

Peng, Y., Wang, Z., and Ai, X. (2018). "Wind-induced fragility assessment of urban trees with structural uncertainties," *Wind and Structures* 26(1), 45-56. DOI: 10.12989/was.2018.26.1.045

Sims, G. D., Nimmo, W., Johnson, A. F., and Ferriss, D. H. (1994). *Analysis of Plate-Twist Test for In-Plane Shear Modulus of Composite Materials (revised)* (NASA STI/Recon Technical Report DMM(a)54*), National Physical Laboratory, Teddington, Middlesex, TN, UK.

Thomas, W. H. (2002). "Shear and flexural deflection equations for OSB floor decking with point load," *Holz als Roh- und Werkstoff* 60(3), 175-180. DOI: 10.1007/s00107-001-0279-4

Timoshenko, S. (1965). *Mechanical Vibration*, China Machine Press, Beijing, China.

Turk, C., Hunt, J., and Marr, D. (2008). *Cantilever-beam Dynamic Modulus for Wood Composite Products* (Research Note FPL-RN-0308), U.S. Department of Agriculture, Forest Service, Forest Products Laboratory, Madison, WI, USA.

Wang, Z., and Wang, Z. (2004). "Application of strain electric method and VB program in measuring bamboo material's elasticity modul E and Poisson ratio μ," *Wood Processing Machinery* 15(1), 16-17. DOI: 10.3969/j.issn.1001-036X.2004.01.005

Wang, Z. (2007). "Dynamic measures of elasticity model and damp ratio to HDF and OSB," *Journal of Nanjing Forestry University (Natural Sciences Edition)* 31(3), 147-149. DOI: 10.3969/j.issn.1000-2006.2007.03.034

Wang, Z., Li, L., and Gong, M. (2012). "Measurement of dynamic modulus of elasticity and damping ratio of wood-based composites using the cantilever beam vibration technique," *Construction and Building Materials* 28(1), 831-834. DOI: 10.1016/j.conbuildmat.2011.09.001

Wang, Z., Wang, Z., Rao, X., Liu, B., and Yang, Y. (2013). "Modulus of elasticity testing of dimensioned SPF lumber and its evaluation based or frequency method," *Journal of Experimental Mechanics* 28(5), 642-648. DOI: 10.7520/1001-4888-12-122

Wang, Z., Gao, Z., Gu, L., Liu, B., Wang, Y., and Yang, Y. (2014a). "Torsional vibration shape method of free plate for testing shear modulus of lumber," *Scientia Silvae Sinicae* 50(11), 122-128. DOI: 10.11707/j.1001-7488.20141117

Wang, Z., Wang, Z., and Brad, J. (2014b). "Dynamic testing and evaluation of modulus of elasticity (MOE) of SPF dimensional lumber," *BioResources* 9(3), 3869-3882. DOI: 10.15376/biores.9.3.3869-3882

Wang, Z., Yang, Y., and Liu, B. (2014c). "Probability distribution of MOE and mechanical properties of SPF dimension lumbers," *Journal of Nanjing Forestry University (Natural Sciences Edition)* 38(2), 157-160. DOI: 10.3969/j.issn.1000-2006.2014.02.030

Wang, Z., Gao, Z., Wang, Y., Cao, Y., Wang, G., Liu, B., and Wang, Z. (2015a). "A new dynamic testing method for elastic, shear modulus and Poisson's ratio of concrete," *Construction and Building Materials* 100, 129-135. DOI: 10.1016/j.conbuildmat.2015.09.060

Wang, Z., Gu, L., Gao, Z., and Liu, B. (2015b). "Dynamic testing and probability distribution of elastic modulus of SPF dimension lumbers," *Scientia Silvae Sinicae* 51(2), 105-111. DOI: 10.11707/j.1001-7488.20150213

Wang, Z., Wang, G., Wang, Y., Cao, Y., and Gao, Z. (2016a). "Determination of shear modulus of wood using free board torsional vibration method," *Journal of Forestry Engineering* 1(4), 10-17. DOI: 10.13360/j.issn.2096-1359.2016.04.002

Wang, Z., Wang, Y., Cao, Y., and Wang, Z. (2016b). "Measurement of shear modulus of materials based on the torsional mode of cantilever plate," *Construction and Building Materials* 124, 1059–1071. DOI: 10.1016/j.conbuildmat.2016.08.104

Wang, Z., Cao, Y., Wang, Y., and Li, M. (2017a). "Testing shear modulus of materials based on torsional mode of cantilever plate," *Scientia Silvae Sinicae* 53(8), 101-112. DOI: 10.11707/j.1001-7488.20170812

Wang, Y., Wang, Z., Li, M., and Cao, Y. (2017b). "Discussion on static testing method of material MDF constants of elastic modulus, Poisson's ratio and shear modulus," *Journal of Beijing Forestry University* 39(10), 117-121. DOI: 10.13332/j.1000-1522.20170107

Wang, Z., Xie, W., Wang, Z., and Cao, Y. (2018). "Strain method for synchronous dynamic measurement of elastic, shear modulus and Poisson's ratio of wood and wood composites," *Construction and Building Materials* 182, 608-619. DOI: 10.1016/j.conbuildmat.2018.06.139

Wang, Z., Fu, H., Ding, Y., Cao, Y., Wang, Y., Wu, X., and Zhang, T. (2019a). "Dynamic testing of shear modulus and elastic modulus of oriented strand board," *Scientia Silvae Sinicae* 55(8), 136-146.

Wang, Z., Fu, H., Ding, Y., Xie, W., Fang, J., Shi, X., Zhao, X., Peng, J., Zhang, T., Zhou, Y., *et al.* (2019b). "A method for measuring wood shear modulus by static torsional strain of square plate," China Patent No. CN109682694A.

Wang, Z., Fu, H., Ding, Y., Xie, W., Rao, X., Yang, J., Fang, J., Shi, X., Zhao, X., Zhang, Y., *et al.* (2019c). "Free square plate torsional mode method for testing shear modulus of wood-based structural panels and wood," China Patent No. CN109900565A.

Wang, Z., Wang, Y., and Cao, Y. (2019d). "Torsion vibration shape method of free plate to test material shear modulus," *Journal of Testing and Evaluation* 42(2), 1163-1181.

Wang, Z., Xie, W., Lu, Y., Li, H., and Wang, Z. (2019e). "Dynamic and static testing methods for shear modulus of oriented strand board," *Construction and Building Materials* 216, 542-551. DOI: 10.1016/j.conbuildmat.2019.05.004

Wang, Z., and Ghanem, R. (2019). "Stochastic sensitivities across scales and physics," *EMI 2019*, 1-4.

Wang, Z., and Ghanem, R. (2021). "An extended polynomial chaos expansion for PDF characterization and variation with aleatory and epistemic uncertainties," *Computer Methods in Applied Mechanics and Engineering* 382(1–4), Article ID 113854.

Wang, Z., and Ghanem, R. (2022). "A functional global sensitivity measure and efficient reliability sensitivity analysis with respect to statistical parameters," *Computer Methods in Applied Mechanics and Engineering* (In Press-Corrected Proof), Article ID 115175. DOI: 10.1016/j.cma.2022.115175

Yin, S. (1996). *Wood Science*, China Forestry Publishing House, Beijing, China.

Yoshihara, H. (2009). "Edgewise shear modulus of plywood measured by square-plate twist and beam flexure methods," *Construction and Building Materials* 23(12), 3537–3545. DOI: 10.1016/j.conbuildmat.2009.06.041

Yoshihara, H., and Sawamura, Y. (2006). "Measurement of the shear modulus of wood by the square-plate twist method," *Holzforschung* 60(5), 543-548. DOI: 10.1515/HF.2006.090

Zhang, L. (1992). *Vibration Test and Dynamic Analysis,* Aviation Industry Press, Beijing, China.

Zhang, Y., Zhu, H., Wang, Z., and Dauletbek, A. (2021). "Analysis of the influence of accelerometer quality and installation position on the test value of wood material constant," *Experimental Techniques* 46, 745-759. DOI: 10.1007/s40799-021-00512-x

Zhou, H., Ren, H., Fei, B., and Jiang, Z. (2007). "Dynamical test on flexural and shear modulus of composite wood panels," *Journal of Building Materials* 10(5), 561-565. DOI: 10.3969/j.issn.1007-9629.2007.05.012

Article submitted: September 22, 2022; Peer review completed: October 22, 2022; Revisions accepted: November 6, 2022; Published: November 16, 2022.
DOI: 10.15376/biores.18.1.Wang