Nondestructive Testing and System Reliability Based on Finite Element Modeling in GFRP-Reinforced Timber Beams

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In the past few decades, the use of glass fiber-reinforced polymers (GFRP) to enhance the strength and stiffness of timber beams has been established. Research to predict the performance of structural timber is ongoing. Nondestructive evaluation of its dynamic performance and reliability are important. A nondestructive testing method based on fast Fourier transform analysis was used to establish the dynamic modulus of elasticity of GFRP-reinforced timber beams. The results were compared to those obtained *via* destructive measurements of the static modulus of elasticity using a regression analysis method. Significant correlations between the dynamic modulus of elasticity (MOE) and static MOE indicate that nondestructive testing is a suitable tool for practical use. Reinforced timber beams were designed based on the measured dynamic MOE. Orthogonal theories were used to analyze the effects of the thickness, glue application, and surface area of GFRP on the MOE of reinforced timber beams. Furthermore, the system reliability of GFRP-reinforced timber beams was predicted with a finite element model. The results showed that GFRP can significantly increase the reliability of structural lumber.

Keywords: Timber beams; Reinforcement; GFRP; MOE; Reliability; Nondestructive testing

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INTRODUCTION

In recent years, many researchers have studied the use of high performance fiber-reinforced polymer (FRP) composites to reinforce timber beams and increase the stiffness and strength of wood-based structural timber (Jasieńko and Nowak 2014; Li *et al.* 2014; Raftery and Whelan 2014). These FRP composites have high strength, are lightweight, are resistant to corrosion, and are electromagnetically neutral, all of which make them suitable candidates for many structural applications, including external wrapping for structural reinforcement and repair purposes (Köroğlu *et al.* 2012). If an economical means of increasing the strength of timber with such composites can be found, it would enable innovative, contemporary wood structures to play a greater role in construction in the future (Yahyaei-Moayyed and Taheri 2011a). Triantafillou and Deskovic (1992) established a new technique for reinforcing wood involving the external bonding of pre-tensioned FRP sheets on their tension zones. They developed an analytical model and verified it with experimental results on carbon/epoxy pre-stressed wood beams. Johns and Lacroix (2000) carried out tests to evaluate the performance of FRP-reinforced wood beams. The results showed that the strength and stiffness of the beams could be increased considerably or even doubled as also shown by other researchers (Davids *et al.* 2000;

Hay *et al.* 2006; Gómez and Svecova 2008). More recently, some researchers bonded pultruded glass fiber-reinforced plastic (GFRP) laminates to glulam beams (Guan *et al.* 2005; Schober and Rautenstrauch 2007; Raftery and Harte 2011; De Jesus *et al.* 2012). These results indicate that GFRP can be considered an effective and economically viable solution for strengthening and stiffening glulam beams, without adding any appreciable weight to the structure (Yusof and Saleh 2010; Osmannezhad *et al.* 2014; Satasivam *et al.* 2014).

Nondestructive evaluation techniques (NDE) have been used to sort and grade wood products in recent decades (Nzokou *et al.* 2006; Lu *et al.* 2013). If the elasticity and strength of wood used in structural applications can be estimated more accurately in a nondestructive way, confidence in the use of wood for structural applications will increase. Moreover, wood can be more appropriately used according to its elasticity and strength (Edwards 2005). Therefore, it is important that the forest industry is able to easily and accurately estimate the elasticity and strength of wood *via* nondestructive testing (Yang *et al.* 2002). Many studies have investigated the dynamic properties of different wood products (Sun and Arima 1999; Hu and Afzal 2006), but little research regarding FRP-reinforced wood products has been conducted (Cheng and Hu 2011a). The modulus of elasticity is an important property of wood and wood-based panel products and is strongly correlated with the reliability of the final timber beams (Rials *et al.* 2002; Hu *et al.* 2005). As reliability-based design of timber structure has become popular, it is becoming more and more important to analyze the reliability with respect to the dynamic modulus of elasticity (MOE). This has practical significance regarding the design and assembly of timber (Cheng and Hu 2011b; Alhayek and Svecova 2012).

As can be seen from the previous brief survey, there have been several studies conducted in consideration of the performance of GFRP reinforced glulam beams. But the effects of GFRP on the dynamic MOE of glulam structural components are relatively scarce. The purpose of this study was to investigate the effects of GFRP thickness, length, and resin content application on the dynamic MOE and to predict the system reliability of GFRP-reinforced timber beams based on the dynamic MOE.

EXPERIMENTAL

Materials

The type of wood lumber was Larch (*Larix gmelinii*). The size was 500 mm (length) ×38 mm(width) ×38 mm (height). The average moisture content of the larch timber was 8.24%, and the coefficient of variation for the moisture content was 12.41%. Variability in the material properties was expected. However, to avoid large inconsistencies, most of the samples were cut from lumber without visual defects (such as knots and grain deviation). The epoxy resin and hardener were supplied by Northeast Forestry University, using the ratio of 4:1. The GFRP composite sheets were supplied by Jianguang Brand (Hebei province, China). To produce the required samples for the characterization of basic mechanical properties, 38-mm-wide strips were extracted from the GFRP sheet with their axes parallel to the fiber direction (Yahyaei-Moayyed and Taheri 2011b). The GFRP of different thicknesses and lengths were bonded to the larch timber beams with various resin content, as shown in Table 1. Twenty-five groups were conducted, each group repeated 3 times. There were 75 GFRP-reinforced larch timber beams.

Table 1. Factors and Levels of Orthogonal Testing

Test Number	Thickness (mm)	Resin content (g/m^2)	Length (mm)
1	0.3	100	125
2	0.3	125	166
3	0.3	150	250
4	0.3	175	333
5	0.3	200	500
6	0.6	100	166
7	0.6	125	250
8	0.6	150	333
9	0.6	175	500
10	0.6	200	125
11	1.0	100	250
12	1.0	125	333
13	1.0	150	500
14	1.0	175	125
15	1.0	200	166
16	1.8	100	333
17	1.8	125	500
18	1.8	150	125
19	1.8	175	266
20	1.8	200	250
21	2.0	100	500
22	2.0	125	125
23	2.0	150	166
24	2.0	175	250
25	2.0	200	333

Numerical Model

Many studies have investigated the development of a finite element model for FRP-reinforced timber (Kim and Harries 2010; Valipour and Crews 2011; Raftery and Harte 2013). A finite element model for GFRP-reinforced timber beams was developed based on dynamic parameters and tested using the FFF analyzer with finite element software ANSYS (Ausiello *et al.* 2002; Doğan 2006). The BEAM3 element was used to simulate the larch timber beams. The properties of the samples were input into the program after building the three-point bending model. The thickness was 38 mm, the length 500 mm, MOE of length direction 5280 Pa, MOE of tangential direction 728 MPa, MOE of radial direction 628 MPa, Poisson's ratio (LT) 0.30, Poisson's ratio (RT) 0.43, and Poisson's ratio (LR) 0.30. The bottom of the sample was selected to be the adhesive surface for the GFRP.

Methods

According to vibration theory, when the length of longitudinal waves is much larger than the cross-sectional dimension of a specimen, the effect of lateral displacement on the longitudinal motion can be neglected without substantial error (Cheng and Hu 2011a). For clear wood specimens, it can be assumed that materials are homogeneous across the longitudinal direction. The dynamic modulus of wood specimens can be determined based on the longitudinal vibration theory of elastic bars (Brancheriau and Baillères 2002; Ilic 2001; Sobue 1986). A hammer was used to tap one end of the specimen, and a microphone received the vibration signal at the other end of the specimen.

The signal was amplified and transmitted to the FFT natural frequency testing system (AD-3452, Onokazu Company, Japan), as shown in Fig. 1. The dynamic MOE of free-free longitudinal vibration, E_p,was calculated (Hu *et al.* 2005). The measurements were carried out in a room maintained at 20 °C and 65% relative humidity.

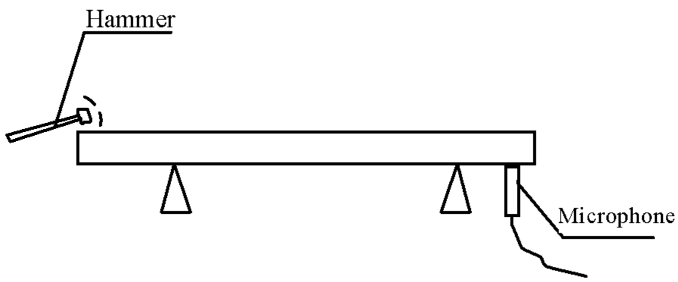


Fig. 1. Test principle of longitudinal resonance

The static MOE of the timber during bending was measured according to Chinese national standard GB/T 17657 (1999), using a universal testing machine (CM T5504, Shen Zhen San Si Co., China) with a 100-kN capacity applying load at a speed of 10 mm/min. The static tension modulus of the GFRP sheet was obtained by tension testing of 10 GFRP specimens according to ISO standard 527-4 (1997). The gauge length for the tension test was 50 mm. The dimensions of the specimens were 250 × 38 × 1.0 mm. The static bending and tensile tests were carried out in a room maintained at 20 °C and 65% relative humidity.

Statistical Analysis

The SPSS software, version 12 (SPSS; Chicago, IL) was used to analyze the influence of different process parameters on the MOE of the samples.

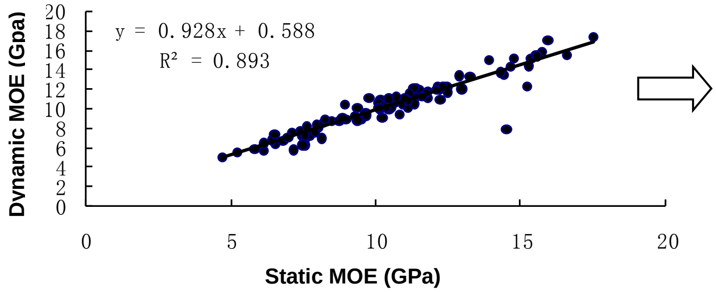
RESULTS AND DISCUSSION

Test Results

Although a nondestructive dynamic vibration method of analysis has many advantages, the static damage detection method was used to test the performance of wood materials to comply with national standards (Ciang *et al.* 2008). Therefore, the relationship between the static elastic modulus and the dynamic modulus of elasticity should be determined. The dynamic MOE in tangential and radial direction was tested. The results of the dynamic MOE and static MOE testing are shown in Table 2.

Regression Analysis

To determine the relationship between the dynamic and static MOE, regression analysis was conducted. The correlation analysis results are shown in Fig. 2. The regression coefficient for the resulting data was 0.893, indicating a strong linear correlation between the dynamic and static MOE. Therefore, nondestructive testing can be used to predict the MOE of GFRP-reinforced timber beams (Yanga *et al*. 2005; Niemz and Manne 2012).



Sample size was 500 mm (length) × 38 mm (width) × 38 mm (height). The GFRP of different thicknesses and lengths were bonded to the larch timber beams with various resin content, as shown in Table 1.

Fig. 2. The correlation analysis of MOE

Table 2. Experimental Data

Test Number	Dynamic MOE (GPa)		Static MOE (GPa)	Test Number	Dynamic MOE (GPa)		Static MOE (GPa)
	Tangential Direction	Radial Direction			Tangential Direction	Radial Direction	
1	13.89	16.02	5.45	39	9.35	8.85	9.22
2	15.97	16.47	3.95	40	12.43	11.47	10.29
3	17.20	15.76	7.08	41	11.68	12.87	8.89
4	16.55	15.36	5.28	42	17.72	17.53	7.19
5	16.06	14.94	2.94	43	14.64	17.08	10.41
6	15.84	15.17	4.89	44	17.64	16.69	10.19
7	12.44	14.85	5.45	45	15.93	15.73	5.28
8	10.73	9.9	4.50	46	17.60	17.46	7.07
9	13.59	15.34	5.77	47	12.92	11.00	9.25
10	12.24	13.24	4.38	48	11.19	9.55	5.02
11	16.97	13.76	3.95	49	13.30	13.3	8.26
12	16.57	17.44	4.05	50	11.77	14.14	6.66
13	16.54	17.42	5.18	51	18.62	13.38	6.49
14	16.34	17.48	4.68	52	13.57	13.62	9.89
15	14.07	15.12	3.3	53	14.23	15.24	6.33
16	14.72	15.44	7.10	54	18.48	15.44	5.66
17	16.10	15.60	4.99	55	18.47	15.83	4.17
18	11.75	11.75	6.06	56	9.84	8.88	8.18
19	13.04	11.84	11.55	57	8.85	8.39	7.59
20	15.15	14.96	8.47	58	16.92	16.74	10.65
21	11.87	11.87	7.62	59	14.10	14.96	5.71
22	12.26	12.91	8.44	60	16.97	15.77	7.82
23	12.16	12.34	10.20	61	14.00	13.62	5.98
24	12.15	11.30	10.68	62	19.03	16.93	8.15
25	15.21	13.26	9.61	63	16.84	15.22	7.10
26	16.80	14.33	3.67	64	11.32	12.56	4.99
27	14.36	14.75	12.79	65	14.57	15.54	5.18
28	13.79	13.95	5.23	66	14.52	15.50	4.68
29	14.92	15.84	11.09	67	12.91	13.49	3.3
30	13.00	13.22	11.58	68	12.96	13.84	7.10

Test Number	Dynamic MOE (GPa)		Static MOE (GPa)	Test Number	Dynamic MOE (GPa)		Static MOE (GPa)
	Tangential Direction	Radial Direction			Tangential Direction	Radial Direction	
31	14.63	13.80	6.77	69	14.37	13.75	4.99
32	15.20	13.36	12.19	70	13.34	13.34	8.47
33	16.21	15.34	11.69	71	10.65	10.90	7.62
34	16.66	17.37	6.22	72	10.99	11.76	8.44
35	15.26	15.76	10.52	73	11.02	11.27	10.20
36	16.41	16.58	3.27	74	10.75	10.25	10.68
37	10.60	11.31	11.79	75	13.90	12.35	9.61
38	9.02	10.31	7.38				

The Effects of GFRP on the MOE

With increasing GFRP thickness, variations in the MOE became smaller. The changes in MOE were obvious with thin values of GFRP. With increasing resin content, variation in the MOE became bigger. The increase in adhesive content also changed the elastic modulus.

With decreasing size of the glue surface, the variation of the elastic modulus value became less obvious. When the surface size was the 1/4 of the length of specimen, the variation in the MOE was larger. It is clear that the surface size should be 1/4 of the length of specimen in future experiments to enhance the effects of GFRP.

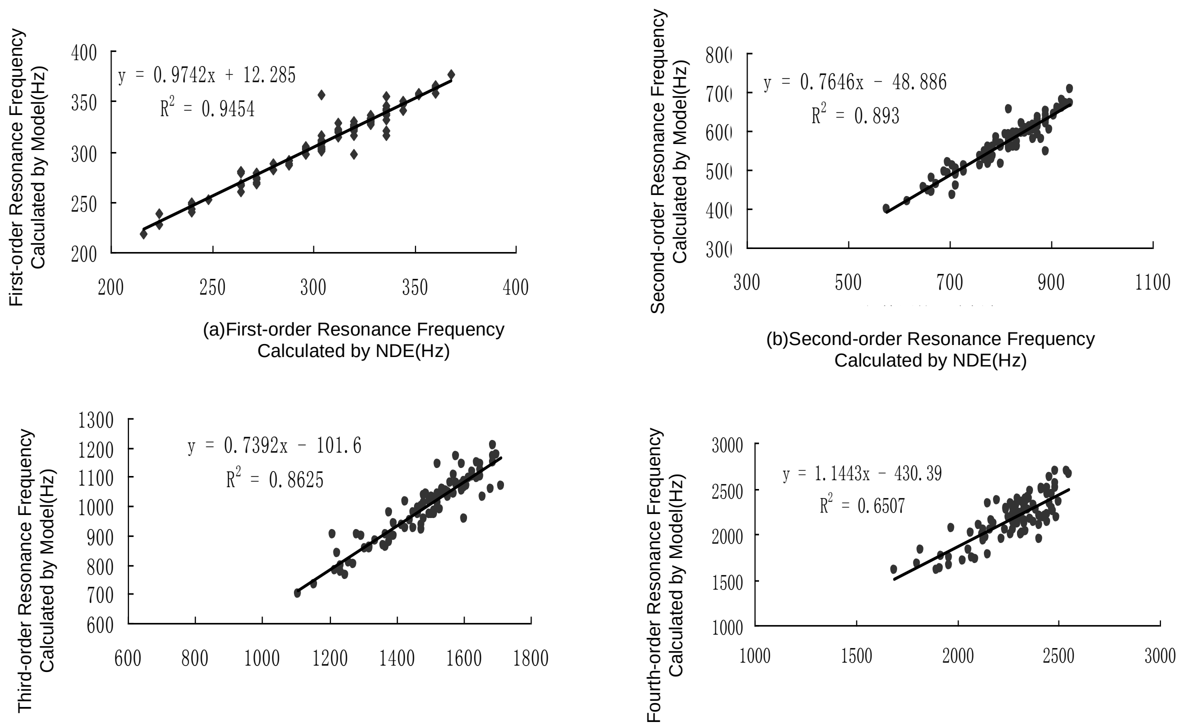
SPSS software was used to analyze the influence of different process parameters on the MOE of the samples, and the results are shown in Table 3. The surface size had the largest influence on the MOE, followed by the glue application and the thickness.

Table 3. Results of Variance Analysis

Source	Type III Sum of Squares	Degrees of Freedom	Mean Square	F	Sig.
Corrected Model	5.106	12	0.426	0.757	0.689
Intercept	66.922	1	66.922	119.036	0.000
Thickness	0.720	4	0.180	0.320	0.863
Glue Application	1.405	4	0.351	0.625	0.648
Surface Area	3.013	4	0.753	1.340	0.272
Error	22.488	40	0.562		
Total	101.234	53			
Corrected Total	27.594	52			

Model Verification

The validity of the finite element model was verified by correlation analysis of the first- to fourth-order resonance frequencies as calculated by the model and the nondestructive vibration detection method. The results of testing of samples are shown in Figs. 3 and 4. As can be seen from the graphs, the first three resonant frequencies had good correlations, but the fourth resonance frequency's correlation was poor. The first three resonant frequencies should therefore be used in nondestructive vibration testing.



(a)First-order Resonance Frequency Calculated by NDE(Hz)

(b)Second-order Resonance Frequency Calculated by NDE(Hz)

(c)Third-order Resonance Frequency Calculated by NDE(Hz)

(d)Fourth-order Resonance Frequency Calculated by NDE(Hz)

Fig. 3. Correlation analysis

Table 4. Reliability of GFRP-Reinforced Lumber Deflection Less than 0.003 L at 425-N Load

Test Number	Average MOE (GPa)	Reliability (%)
1	9.82	100.0
2	8.67	98.4
3	9.27	97.2
4	9.09	96.0
5	8.08	90.1
6	8.68	94.4
7	10.29	100.0
8	9.59	89.5
9	8.84	96.1
10	9.80	99.3
11	9.11	98.4
12	9.58	97.0
13	9.65	99.1
14	8.44	94.4
15	11.18	100.0
16	9.26	88.4
17	10.03	100.0
18	9.55	97.4
19	9.74	98.1
20	9.71	98.0
21	8.77	95.8
22	9.26	96.8
23	8.72	95.6
24	8.58	95.2
25	8.51	95.0

CONCLUSIONS

1. The surface size had the greatest effect on the MOE, followed by the glue application and the thickness. The laminate size should be larger than 1/4 the length of the specimen in future experiments.
2. Finite element models were developed to simulate the reliability of a GFRP-reinforced timber beam system. The probability of material deflection less than 0.003 L is 9% at a 425-N load, and the reliability of FRP is 53.8%. The probability of material deflection less than 0.005 L is 71.6%, and the FRP reliability is 97.3%. GFRP can significantly increase the reliability of wooden structural lumber.

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REFERENCES CITED

Alhayek, H., and Svecova, D. (2012). "Flexural stiffness and strength of GFRP-reinforced timber beams," *Journal of Composites for Construction* 16(3), 245-252.
Amy, K., and Svecova, D. (2004). "Strengthening of dapped timber beams using glass fibre reinforced polymer bars," *Canadian Journal of Civil Engineering* 31(6), 943-955.
Ausiello, P., Apicella, A., and Davidson, C. L. (2002). "Effect of adhesive layer properties on stress distribution in composite restorations-A 3D finite element analysis," *Dental Materials* 18(4), 295-303.
Brancheriau, L., and Baillères, H. (2002). "Natural vibration analysis of clear wooden beams: A theoretical review," *Wood Science and Technology* 36(4), 347-365.
Cheng, F., and Hu, Y. (2011a). "Nondestructive test and prediction of MOE of FRP reinforced fast-growing poplar glulam," *Composites Science and Technology* 71(8), 1163-1170.
Cheng, F., and Hu, Y. (2011b). "Reliability analysis of timber structure design of poplar lumber with nondestructive testing methods," *BioResources* 6(3), 3188-3198.
Ciang, C. C., Lee, J. R., and Bang, H. J. (2008). "Structural health monitoring for a wind turbine system: A review of damage detection methods," *Measurement Science and Technology* 19(12), 1-20.
Davids, W. G., Dagher, H. J., and Breton, J. M. (2000). "Modeling creep deformations of FRP-reinforced glulam beams," *Wood and Fiber Science* 32(4), 426-441.
De Jesus, AMP, Pinto JMT, and Morais J. J. L. (2012). "Analysis of solid wood beams strengthened with CFRP laminates of distinctive lengths," *Construction and Building Materials* 35: 817-828.
Doğan, T. (2006). *Prediction of Composite Vessels under Various Loadings*, M.S. thesis, Graduate School of Natural and Applied Sciences, Dokuz Eylül University, Izmir, Turkey.

Edwards, K. (2005). “Selecting materials for optimum use in engineering components,” *Materials and Design* 26(5), 469-473.

GB/T17657. (1999). “Test methods of evaluating the properties of wood-based panels and surface decorated wood-based panels,” *Chinese National Standard, General Administration of Quality Supervision, Inspection and Quarantine of China*.

Gómez, S., and Svecova, D. (2008). “Behavior of split timber stringers reinforced with external GFRP sheets,” *Journal of Composites for Construction* 12(2), 202-211.

Guan, Z., Rodd, P., and Pope, D. (2005). “Study of glulam beams pre-stressed with pultruded GRP,” *Computers and Structures* 83(28), 2476-2487.

Hay, S., Thiessen, K., Svecova, D., and Bakht, B. (2006). “Effectiveness of GFRP sheets for shear strengthening of timber,” *Journal of Composites for Construction* 10(6), 483-491.

Hu, C., and Afzal, M. T. (2006). “A statistical algorithm for comparing mode shapes of vibration testing before and after damage in timbers,” *Journal of Wood Science* 52(4), 348-352.

Hu, Y., Wang, F., Gu, J., Liu, Y., and Nakao, T. (2005). “Nondestructive test and prediction of modulus of elasticity of veneer-overlaid particleboard composite,” *Wood Science and Technology* 39(6), 439-447.

Ilic, J. (2001). “Relationship among the dynamic and static elastic properties of air-dry *Eucalyptus delegatensis* R. Baker,” *Holz als Roh-und Werkstoff* 59(3), 169-175.

ISO 527-4. (1997). “Plastics-determination of tensile properties - Part 4: Test conditions for isotropic and orthotropic fibre-reinforced plastic composites,” *British Standards Institution*, London.

Jasieńko, J., and Nowak, T. P. (2014). “Solid timber beams strengthened with steel plates – Experimental studies,” *Construction and Building Materials* 63, 81-88.

Kim, Y. J., and Harries, K. A. (2010). “Modeling of timber beams strengthened with various CFRP composites,” *Engineering Structures* 32(10), 3225-3234.

Köroğlu, M. A., Ceylan, M., Arslan, M. H., and İlki, A. (2012). “Estimation of flexural capacity of quadrilateral FRP-confined RC columns using combined artificial neural network,” *Engineering Structures* 42(9), 23-32.

Li, Y. F., Tsai, M. J., Wei, T. F., and Wang, W. C. (2014). “A study on wood beams strengthened by FRP composite materials,” *Construction and Building Materials* 62, 118-125.

Lu, W., Yao, J., Liu, X., Ma, L., and Wang, Y. (2013). “Nondestructive testing and performance prediction of soybean stalk board,” *BioResources* 8(4), 4794-4804.

Niemz, P., and Mannes, D. (2012). “Non-destructive testing of wood and wood-based materials,” *Jourmal of Cultural Heritage* 138, 26-34.

Nzokou, P., Freed, J., and Kamdem, D. P. (2006). “Relationship between non destructive and static modulus of elasticity of commercial wood plastic composites,” *Holz als Roh-und Werkstoff* 64(2), 90-93.

Osmannezhad, S., Faezipour, M., and Ebrahimi, G. (2014). “Effects of GFRP on bending strength of glulam made of poplar (*Populus deltoids*) and beech (*Fagus orientalis*),” *Construction and Building Materials* 51(31), 34-39.

Raftery, G. M., and Harte, A. M. (2011). “Low-grade glued laminated timber reinforced with FRP plate,” *Composites Part B: Engineering* 42(4), 724-735.

Raftery, G. M., and Harte, A. M. (2013). “Nonlinear numerical modeling of FRP plate reinforced glued laminated timber,” *Composites Part B: Engineering* 52, 40-50.

Raftery, G. M., and Whelan, C. (2014). "Low-grade glued laminated timber beams reinforced using improved arrangements of bonded-in GFRP rods," *Construction and Building Materials* 52, 209-220.

Rials, T. G., Kelley, S. S., and So, C. L. (2002). "Use of advanced spectroscopic techniques for predicting the mechanical properties of wood composites," *Wood and Fiber Science* 34(3), 398-407.

Schober, K. U., and Rautenstrauch, K. (2007). "Post-strengthening of timber structures with CFRP's," *Materials and Structures* 40(1), 27-35.

Satasivam, S., Bai,Y., and Zhao, X. L. (2014). "Adhesively bonded modular GFRP web–flange sandwich for building floor construction," *Composite Structures*111, 381-392.

Sobue, N. (1986). "Measurement of Young's modulus by the transient longitudinal vibration of wooden beams using a fast Fourier transformation spectrum analyzer," *Journal of the Japan Wood Research Society* 32(9), 744-747.

Sun, Y. G., and Arima, T. (1999). "Structural mechanics of wood composite materials. 11: Ultrasonic propagation mechanism and internal bonding of particleboard," *Journal of Wood Science* 45(3), 221-226.

Valipour, H. R., and Crews, K. (2011). "Efficient finite element modeling of timber beams strengthened with bonded fibre reinforced polymers," *Construction and Building Materials* 25(8), 3291-3300.

Yahyaei-Moayyed, M., and Taheri, F. (2011a). "Creep response of glued-laminated beam reinforced with pre-stressed sub-laminated composite," *Construction and Building Materials* 25(5), 2495-2506.

Yahyaei-Moayyed, M., and Taheri, F. (2011b). "Experimental and computational investigations into creep response of AFRP reinforced timber beams," *Composite Structures* 93(2), 616-628.

Yang, X., Ishimaru, Y., Iida, I., and Urakami, H. (2002). "Application of modal analysis by transfer function to nondestructive testing of wood I: Determination of localized defects in wood by the shape of the flexural vibration wave," *Journal of Wood Science* 48(4), 283-288.

Yusof, A., and Saleh, A. L. (2010). "Flexural strengthening of timber beams using glass fibre reinforced polymer," *Electron. J. Struct. Eng.* 10(1), 45-56.

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