Evaluation of Mechanical Properties of Reinforced Poplar Laminated Veneer Lumber

Jie Wang,[a] Xiaolei Guo,[a] Wei Zhong,[b] Huiyun Wang,[a] and Pingxiang Cao [a,*]

Three types of reinforcement materials, a carbon fiber-reinforced polymer (CFRP) sheet, a glass fiber-reinforced polymer (GFRP) mesh, and a composite of the CFRP sheet and GFRP mesh, were used to reinforce poplar laminated veneer lumber (LVL), and the multi-step hot-pressing method was also applied. The mechanical properties, *i.e.*, modulus of rupture (MOR), modulus of elasticity (MOE), and horizontal shear strength (HSS), of the reinforced LVL were investigated, as well as the effects of lay-up location of the CFRP sheet/GFRP mesh composite. The results indicated that applying the multi-step hot-pressing method and incorporating the CFRP sheet, GFRP mesh, and the CFRP sheet/GFRP mesh composite noticeably improved the MOR and MOE under horizontal and vertical loadings. Only the multi-step hot-pressing method was able to greatly improve the HSS of reinforced LVL under both loading modes. The improved effect of the three kinds of reinforcing materials on the mechanical properties was ordered as follows: CFRP sheet/GFRP mesh composite > CFRP sheet > GFRP mesh. Locating the CFRP sheet/GFRP mesh composite closer to the surface veneer layer yielded the best mechanical properties for the reinforced poplar LVL.

Keywords: Poplar laminated veneer lumber; Carbon fiber sheet; Glass fiber mesh; Multi-step hot pressing method; Mechanical properties

*Contact information: a: Faculty of Material Science and Engineering, Nanjing Forestry University, Nanjing 210037, China; b: Guangzhou Homebon Timber Manufacturing Co., Ltd., Guangzhou 511480, China; *Corresponding author: caopx@njfu.com.cn*

INTRODUCTION

In China, because of the serious shortage of high-quality timber from natural forests, poplar is a widely planted and fast-growing species that has become one of the main resources in the wood industry (Xu 2014). However, its loose material and low mechanical properties limit its application in structural products. Developing the advanced technology to improve the performance of poplar products and to expand the scope of the application of poplar products are two very important goals.

Laminated veneer lumber (LVL) is a wood product similar to plywood, but, unlike plywood, is a parallel-laminated veneer (Laufenberg 1983; Wei and Zhou 2012). Because of its excellent performance properties, such as good dimensional stability, uniform strength, adaptability to engineering, free size design, and suitability for automatic production, LVL is a high-quality product that has been used in both non-structural and structural applications, such as the flooring industry, the furniture industry, packaging, and construction (Sasaki 2001; Anonymous 2009; Mei and Zhou 2009; Tenorio *et al.* 2011; Wei and Zhou 2012). However, because of the poor performance properties of poplar, poplar LVL is rarely used as a structural timber.

Reinforcing technology is a feasible and effective method for improving the mechanical properties of LVL made of low-quality, fast-growing wood. As a result, reinforced LVL can be an alternative to high-quality solid wood timber. Over many years, various studies have been conducted regarding the reinforcement of LVL. Laufenberg *et al.* (1984) analyzed the economic feasibility of reinforcing LVL with synthetic fibers. The evaluation indicated that there were great advantages in using glass fiber to reinforce LVL. Pirvu *et al.* (2004) investigated the interface properties of a carbon FRP-wood hybrid composite and the mechanical and physical properties retention of a carbon/vinyl ester composite after preservative treatments. Wei *et al.* (2013) studied the modulus of rupture and the modulus of elasticity of poplar LVL reinforced by carbon-fiber-reinforced polymer (CFRP) in two different configurations. The results showed that poplar LVL reinforced by a single layer of CFRP on one side had higher bending strength than that reinforced by a single layer of CFRP on each side. Buell and Saadatmanesh (2005) researched the effects of carbon fiber fabric on the strengthening of timber bridge beams to increase their load capacity. The results indicated that the stiffness, bending, and shear strength of beams reinforced by carbon fiber fabric showed greater increases when compared with the un-reinforced beams and concluded that carbon fiber fabric could reduce the effects of wood defects on the mechanical properties of the beams. Kim *et al.* (2010) investigated the influence of various CFRP properties on the behavior of the various timber species and found that the energy absorption capacity of the reinforced beams were greater than those of the non-reinforced beams. Zhou *et al.* (2015) studied the influence of moisture on the performance of the entire CFRP-wood composite system and found that the strength of the interface determined the mechanical properties of the CFRP-wood composite and that water absorption was very important for the durability of the entire CFRP-wood composite system. Bal (2014) studied the effects of woven glass fiber on the mechanical properties of reinforced LVL. The study found that making use of woven glass fiber to reinforce LVL had some positive influences and some negative influences on the mechanical properties. Wang *et al.* (2011) introduced an investigation to reinforce LVL with ramie fiber. The study indicated that using ramie fiber to enhance LVL could improve the mechanical properties of LVL, especially the level of shear strength. Zhang and Hu (2010) studied the influence of the lay-up position of glass fiber mesh on improvements in the mechanical properties, and three useful methods to predict the MOE of reinforced LVL were tested. Raftery and Harte (2011) found that the reasonable usage of GFRP to enhance low-grade glued laminated timber could improve the stiffness and the ultimate moment capacity, and the utilization of compression strength was increased. Hu *et al.* (2010) investigated the effects of various factors on the mechanical properties of LVL reinforced by metal mesh, showing that the lay-up position and coarseness of the metal mesh greatly effected MOE and the type and lay-up position of the metal mesh significantly influenced the MOR. In addition, many other methods of reinforcing LVL have been studied, such as veneer densification using impregnation, and adding bamboo veneer into LVL. All of these methods have been shown to be effective at reinforcing the mechanical properties of LVL (Zhu *et al.* 2005; Liu *et al.* 2007; Liu *et al.* 2009; Haller *et al.* 2015).

Although many studies have been done to investigate the methods of reinforcing LVL, applying the composite of the carbon sheet/glass fiber mesh and multi-step hot pressing method to reinforce LVL has not been widely reported. Furthermore, researching the reinforcement effect of different reinforcement materials on improving LVL mechanical properties is very important from the perspective of designing high-quality LVL with low cost. The aims of the present study were as follows: 1) to investigate the effects of the inclusion of a carbon fiber sheet/glass fiber mesh composite, carbon fiber sheet, and glass fiber mesh on the mechanical properties of reinforced poplar LVL; 2) to compare the reinforcement effects of these three reinforcement materials on poplar LVL; 3) to study the influence of the multi-step hot-pressing method on the mechanical properties of reinforced poplar LVL; and 4) to study the effects of lay-up position of the reinforcement carbon fiber sheet/glass fiber mess composite on the mechanical properties of reinforced poplar LVL.

EXPERIMENTAL

Materials and Specimens

The poplar veneers were provided by Peace Wood Co., Ltd., located in Xuzhou, Jiangsu Province, China. The dimensions of the poplar veneers were 1220 mm (length) × 1220 mm (width) × 3.2 mm (thickness), the average moisture content was approximately 7.8%, and the average density was 0.402 g/cm^3. A phenol formaldehyde adhesive (PF), provided by Dynea Guangdong Co., Ltd., was chosen to glue the laminated veneer lumber (LVL); its solids content was 43.52%. Alkali-free glass fiber (E-glass fiber) mesh was provided by Hejian Deliyuan Fiberglass Products Co., Ltd. The E-glass fiber mesh size was 4 mm × 4 mm, and its unit weight was approximately 150 g/m^2. A pan-carbon fiber sheet, whose specification was 1 k, was chosen as one of the reinforcement materials; this was provided by Liso Composite Material Technology Co., Ltd. A silane coupling agent of grade A-1100, whose mass fraction was 97%, was selected for the surface treatment of the carbon fiber sheet and glass fiber mesh. All reinforced poplar LVLs were manufactured on a multi-layer hot-pressing press machine (BY214*8/6-15, China) at Guangzhou Homebon Timber Manufacturing Co., Ltd.

Methods

Reinforced poplar LVL manufacturing process

The reinforced LVL was fabricated as follows. First, carbon fiber sheets and glass fiber meshes were soaked in a silane coupling agent aqueous solution for 15 min. The mass fraction of the silane coupling agent aqueous solution was 2%. Second, the carbon fiber sheets and glass fiber meshes were dried in an electrothermal constant temperature drying cabinet at 120 °C for 20 min. Third, PF was spread over the poplar veneer with a roller. Fourth, the nine-layer poplar veneers spread with PF, the carbon fiber sheets, and the glass fiber meshes were laminated parallel to the grain direction. The poplar veneers were laminated in accordance with the rule of face-to-face and back-to-back. Fifth, the composite was pre-pressed in a cold press for 30 min to allow part of the PF to penetrate into the poplar veneer. The pre-pressing was also used to decrease the total thickness of the composite, which would help position the composite in the hot-pressing machine. Sixth, the composite was hot-pressed at 140 °C until the PF had cured.

For both processes, the veneer resin content of each side was 160 g/m^2. The manufacturing parameters used when reinforcing poplar LVL *via* the multi-step hot-pressing method are shown in Table 1. For the reinforcement of poplar LVL with the glass fiber mesh and carbon fiber sheet, the manufacturing parameters were established as follows: pre-pressing pressure of 1.0 MPa, hot-pressing pressure of 1.2 MPa, hot-pressing time of 100 s/mm, and hot-pressing temperature of 140 °C±5 °C.

The dimensions of the products were 1220 mm (length) × 610 mm (width) × 24 mm (thickness). A total of six types of reinforced poplar LVL and one type of non-reinforced poplar LVL (a control LVL) were produced. The control LVL and LVL reinforced by reinforcing materials were manufactured with one-step hot pressing method. The dimensions of the specimens were in accordance with the Chinese National Standard GB/T 20241-2006 (2006).

Table 1. Pressing Parameters of Multi-Step Hot-pressing Method

Pressing stage	Pressing pressure (MPa/m²)	Pressing temperature (°C)	Pressing time
Pre-pressing	1.0	ambient temperature	30 min
First stage of hot-pressing	1.0	140±5	100 s/mm
Second stage of hot-pressing	1.2	140±5	80 s/mm

The type of poplar LVL reinforced by multi-step hot pressing method (LVL-MH) just consisted of nine-layer poplar veneers. The manufacturing process when using the multi-step hot pressing method to reinforce the poplar LVL and the structure of this type of reinforced LVL are shown in Fig. 1.

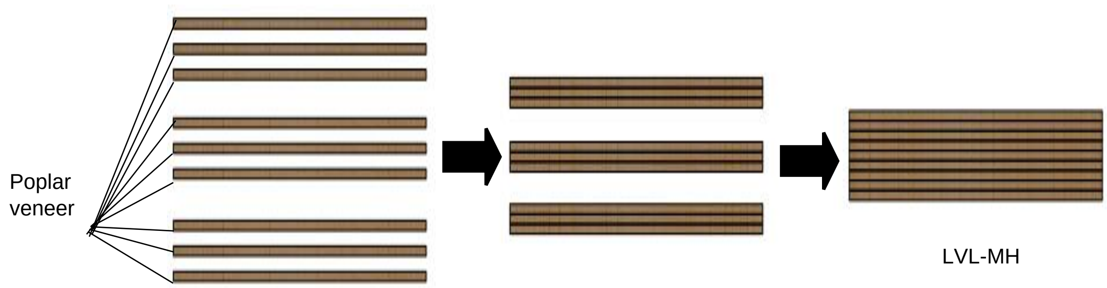

Fig. 1. The manufacturing process for the multi-step hot pressing method

All types of LVL reinforced by reinforcement materials that were used in the study are shown in Fig. 2. The first type just consisted of nine-layer poplar veneers, and this type of LVL was manufactured as a control (LVL-CG) in this study (Fig. 2A). The second type (LVL-CS+GM) was made of nine-layer poplar veneers, eight-layer CFRP sheets, and eight-layer GFRP meshes, the CFRP sheet/GFRP mesh composite for LVL-CS+GM was laid up between all veneers symmetrically (Fig. 2B). The third type (LVL-GM) was composed of nine-layer poplar veneers and eight-layer GFRP meshes, the GFRP mesh for LVL-GM was laid up between all veneers (Fig. 2C). The fourth type (LVL-CS) was composed of nine-layer poplar veneers and eight-layer CFRP sheets, the CFRP sheet for LVL-CS was laid up between all veneers (Fig. 2D). The fifth and sixth types (LVL-SD and LVL-CD) both consisted of nine-layer poplar veneers, two-layer CFRP sheets, and two-layer GFRP meshes; the reinforcement of the CFRP sheet/GFRP mesh composite for LVL-SD was laid up near to the surface veneer symmetrically (Fig. 2E); the reinforcement of the CFRP sheet/GFRP mesh composite for LVL-CD was laid up near to the core veneer symmetrically (Fig. 2F).

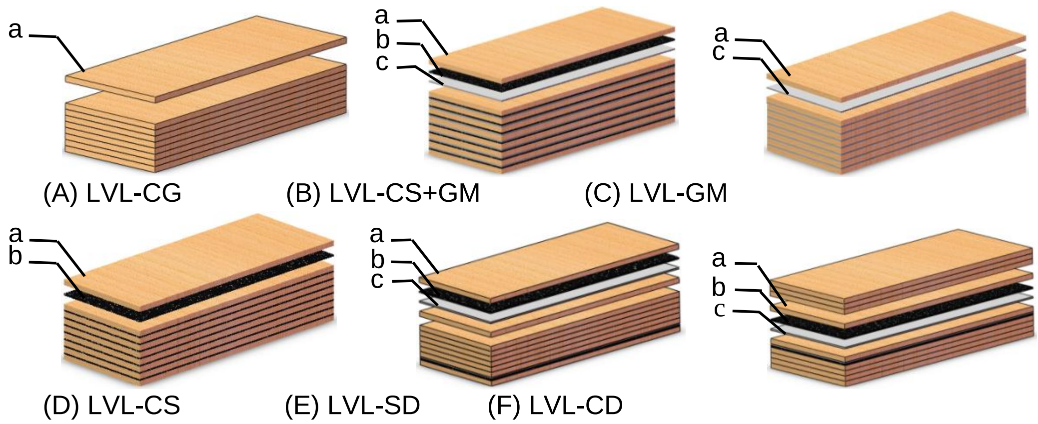

Fig. 2. Six types of poplar LVL for construction: (A), (B), (C), (D), (E), and (F); (a) poplar veneer, (b) CFRP sheet, and (c) GFRP mesh

In addition to the control group LVL-CG, six other types of reinforced LVL were worked as the experiment groups. LVL-MH was made for studying on the effect of multi-step hot pressing method on improving mechanical properties of poplar LVL. LVL-CS+GM, LVL-GM, and LVL-CS were made for researching on the improvement effect of different kinds of reinforcement materials on mechanical properties for reinforced poplar LVL. LVL-SD and LVL-CD were made in order to study the improvement effect of different lay-up locations of reinforcement materials on mechanical properties for reinforced poplar LVL.

Measurement of mechanical properties

The mechanical properties examined in this research included the modulus of rupture (MOR), modulus of elasticity (MOE), and horizontal shear strength (HSS). For each mechanical property, both the horizontal loading and the vertical loading modes were tested. Thus, this research investigated the values of MOR, MOE, and HSS under horizontal loading (MOR_H, MOE_H, and HSS_H) and the values of MOR, MOE, and HSS under vertical loading (MOR_V, MOE_V, and HSS_V). Three replicates were used, yielding a total of 21 LVL billets.

Testing specimens were cut from each billet according to the Chinese National Standard GB/T 20241-2006 (2006). The dimension of specimens for MOR_H and MOE_H was 600 mm × 25 mm × 25 mm (Length × Width × Thickness). The dimension of specimens for MOR_V and MOE_V was 600 mm × 90 mm × 25 mm (Length × Width × Thickness). The dimension of specimens for HSS_H was 150 mm × 25 mm × 25 mm (Length × Width × Thickness). The dimension of specimens for HSS_V was 150 mm × 40 mm × 25 mm (Length × Width × Thickness).

The mechanical properties were measured using a wood electronic universal testing machine (WDW-100D, China). The methods used to measure the mechanical properties were in accordance with the Chinese National Standard GB/T 20241-2006 (2006).

RESULTS AND DISCUSSION

Analysis of the Effects of Multi-Step Hot-pressing Method on the Mechanical Properties of Reinforced Poplar LVL

Table 2 shows the measured values of MOR, MOE, and HSS for the non-reinforced LVL (LVL-CG) and for the poplar LVL that had been reinforced using the multi-step hot-pressing method (LVL-MH). One-way ANOVA showed that there was a significant difference at a 99% confidence among the mechanical properties.

Table 2. Mechanical Properties of Poplar LVL Reinforced by the Multi-Step Hot-Pressing Method

Reinforcement type	MOR_H (MPa)		MOR_V (MPa)		MOE_H (MPa)		MOE_V (MPa)		HSS_H (MPa)		HSS_V (MPa)	
	Mean	Std. dev	Mean	Std. dev	Mean	Std. dev	Mean	Std dev	Mean	Std. dev	Mean	Std dev
LVL-CG	90.5	5.09	79.9	4.02	9185.8	128.04	8362.0	185.70	9.7	0.21	10.9	0.74
LVL-MH	124.2	3.75	110.3	2.90	11024.0	364.08	11517.0	186.19	12.7	0.47	14.4	0.63

Table 2 shows that the values of MOR_H, MOE_H, HSS_H, MOR_V, MOE_V, and HSS_V of the LVL-MH were higher than those of the control group, LVL-CG, by 37.23%, 38.04%, 20.01%, 37.73%, 30.93%, and 32.11%, respectively. These results may have occurred because six resin layers, among the total eight layers, were hot-pressed twice, such that the resin was able to cure further. All the veneers of the LVL were hot-pressed twice, which led to an increase in the density of the veneers. Several studies have found that, as long as the amount of compression applied to a wood veneer remains below its compression strength limit, greater compression values, and consequently, higher values of veneer density, are associated with higher values of MOE and MOR (Li *et al.* 2010; Zhang *et al.* 2012).

Analysis of the Effects of CFRP Sheet and GFRP Mesh on the Mechanical Properties of Poplar LVL

Values of the mechanical properties, MOR, MOE, and HSS, for various types of poplar LVL that were reinforced using CFRP sheet and GFRP mesh are listed in Table 3.

Table 3. Measured Values of the Mechanical Properties for Various Types of Reinforced Poplar LVL

Reinforce-ment type	MOR_H (MPa)		MOR_V (MPa)		MOE_H (MPa)		MOE_V (MPa)		HSS_H (MPa)		HSS_V (MPa)	
	Mean	Std. dev	Mean	Std. dev	Mean	Std. dev	Mean	Std. dev	Mean	Std. dev	Mean	Std. dev
LVL-CG	90.5	5.09	79.9	4.02	9185.8	128.04	8362.0	185.70	9.7	0.21	10.9	0.74
LVL-GM	106.9	7.67	91.8	5.29	10365.0	97.61	9273.5	366.75	12.5	0.54	10.2	1.28
LVL-CS	113.7	5.96	105.4	5.53	11016.5	163.62	9992.5	408.21	13.1	0.34	11.4	1.02
LVL-CS+GM	129.4	4.03	115.1	6.06	12544.0	230.47	10635.0	373.03	14.0	1.12	10.0	1.47

One-way ANOVA showed that there was a significant difference at a 99% confidence among MOE_H, MOE_V, MOR_H, MOR_V, and HSS_H. There was no significant difference among HSS_V. Figure 3 shows the percentages of improvement in mechanical properties for the three types of reinforced poplar LVL.

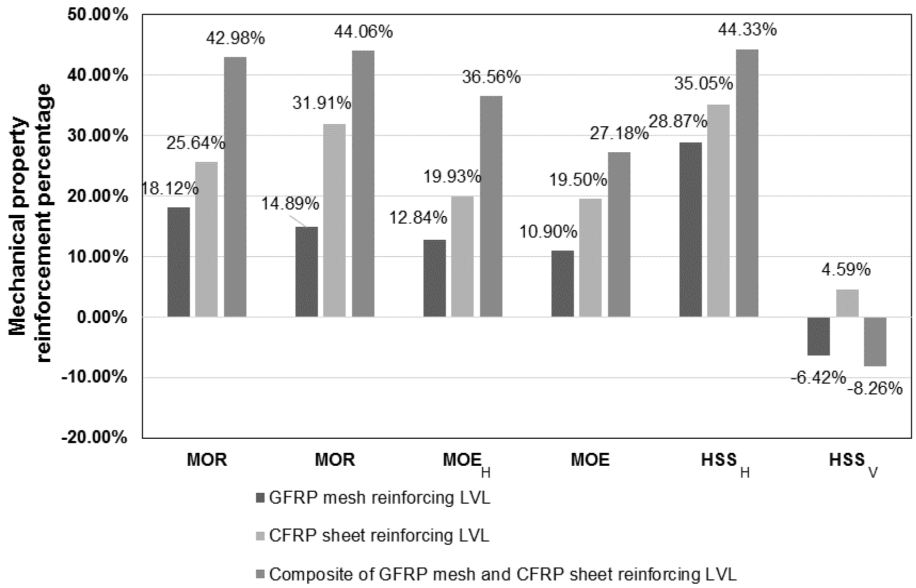

Fig. 3. Percentage of improvement in mechanical properties in comparison to control for three types of reinforced poplar LVL

Figure 3 illustrates the effects of reinforcement materials on the MOR, MOE, and HSS of reinforced poplar LVL. Mechanical properties of three types of reinforced LVL were higher than that of the control group. The tensile strength (TS) and MOE of glass fiber mesh and carbon fiber sheet are higher than for wood veneer, so using glass fiber mesh and carbon fiber sheet could improve the mechanical properties of LVL. Secondly, applying the glass fiber mesh, carbon fiber sheet, and the composite of the carbon fiber sheet/glass fiber mesh to reinforce LVL could increase its average density or compression ratio when the thickness was constant. Increasing compression ratio resulted in increasing in mechanical properties. Wang and Dai (2005) showed that compression ratio (lower than 10%) increased by 1%, which led to an approximately 1% increase in aspen LVL stiffness. Wei *et al.* (2013) found that an increase in compression ratio of LVL would improve MOE of LVL.

Among the three types of reinforced LVL, the LVL-CS+GM showed the highest degree of improvement in all mechanical properties except for HSS_V. In addition, LVL-CS showed greater improvement in mechanical properties than did LVL-GM. The results can be attributed to the following factors: firstly, the values of TS and MOE for E-glass fiber (TS: 3.4GPa; MOE: 72.3GPa) in this research were lower than that of Pan-carbon fiber (TS: 3.93GPa; MOE: 221GPa), so the reinforcement effect on LVL mechanical properties of Pan-carbon fiber was greater than that of E-glass fiber. Secondly, the composite of the carbon fiber sheet /glass fiber mesh had better mechanical properties compared to carbon fiber and glass fiber, and also the composite had the effect of compound enhancement between carbon fiber sheet and glass fiber mesh, which led to increasing load-carrying capacity of LVL-CS+GM. So LVL-CS+GM had the best mechanical properties. Thirdly, due to the low surface activity of glass fiber sheet, bonding strength of LVL-GM and LVL-CS+GM was lower than LVL-CG, so HSS_V of LVL-GM and LVL-CS+GM decreased compared to LVL-CG. Therefore, the degrees of improvement in mechanical properties, excluding HSS_V, for the three reinforcement types were ordered as follows: LVL-CS+GM > LVL-CS > LVL-GM.

Analysis of the Effects of Lay-up Location of Reinforcing Materials on the Mechanical Properties of Poplar LVL

To study the effect of the lay-up location of the reinforcing composite material on the mechanical properties of the poplar LVL, two types LVL-SD and LVL-CD of reinforced poplar LVL were designed, as presented in Fig. 2 (E) and (F). The measured values of the mechanical properties for LVL-SD and LVL-CD are shown in Table 4. One-way ANOVA showed that there was a significant difference at a 99% confidence among MOE_H, MOE_V, MOR_H, and MOR_V. There was a significant difference at a 95% confidence among HSS_H, and HSS_V. The percentages of improvement in mechanical properties for the LVL-SD and LVL-CD are shown in Fig. 4.

Table 4. Measured Values of Mechanical Properties of Reinforced Poplar LVL with Various Lay-Up Locations of Reinforcement Material

Lay-up location	MOR_H (MPa)		MOR_V (MPa)		MOE_H (MPa)		MOE_V (MPa)		HSS_H (MPa)		HSS_V (MPa)	
	Mean	Std. dev	Mean	Std. dev	Mean	Std. dev	Mean	Std. dev	Mean	Std. dev	Mean	Std dev
LVL-CG	90.5	5.09	79.9	4.02	9185.8	128.04	8362.0	185.70	9.7	0.21	10.9	0.74
LVL-SD	113.8	4.31	109.4	6.43	10941.0	316.09	10289.5	393.57	12.2	0.73	11.1	1.09
LVL-CD	103.2	6.52	100.7	9.34	10076.3	182.15	9672.0	585.70	11.7	0.42	11.0	0.47

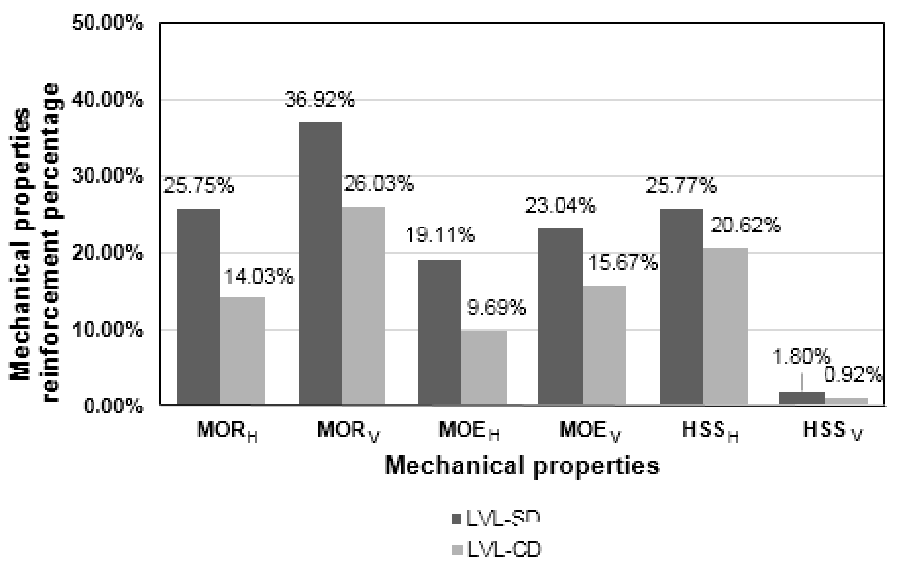

Fig. 4. Percentages of improvement in mechanical properties in comparison to control for LVL-SD and LVL-CD

As can be seen in Fig. 4, LVL-SD could be used to obtain better mechanical properties than could LVL-CD. However, HSS_V did not improve with the use of these forms of reinforced poplar LVL. According to the mechanics theory of composite materials (Shen *et al.* 2006), maximum stress would occur on the outermost layer of LVL specimens during bending. When reinforcement material was laid closer to the outer layer veneer, the influence of the reinforcement material on improving mechanical properties was more significant, and the larger load-carrying capacity would be obtained. In other words, locating the composite of CFRP and GFRP closer to the surface veneer layer yielded better mechanical properties for poplar LVL, which agrees with the research conclusions of Mei and Zhou (2009).

CONCLUSIONS

1. Under both horizontal and vertical loading modes of poplar LVL, all tested mechanical properties, *i.e.*, MOR, MOE, and HSS, were greatly improved by the use of the multi-step hot-pressing method for the reinforcement of LVL.
2. When the mechanical properties of LVLs reinforced by different materials (CFRP sheet/GFRP mesh composite, CFRP sheet, and GFRP mesh) were compared, it was possible to conclude that for all types of reinforced LVL, in comparison to the control LVL, MOR and MOE were improved under horizontal loading and vertical loading, and HSS was improved under horizontal loading, but became less desirable under vertical loading.
3. The poplar LVL reinforced by the CFRP sheet/GFRP mesh composite exhibited the highest MOR and MOE. The poplar LVL reinforced by the CFRP sheet showed the second highest MOR and MOE. The poplar LVL reinforced by GFRP mesh exhibited the lowest MOR and MOE of the three types of reinforced LVL.
4. Better mechanical properties were found for the poplar LVL when a symmetrical lay-up location was used for the reinforcing material and when the CFRP sheet/GFRP mesh composite was located closer to the surface veneer layer.

ACKNOWLEDGMENTS

The authors are grateful for the support from the Science and Technology Project of Jiangsu Province (No. BY2015006-04) and the National Science and Technology Support Plan of China (No. 2012BAD24B01) and the Priority Academic Program Development of the Jiangsu Higher Education Institutions (PAPD).

REFERENCES CITED

United Nations Economic Commission for Europe and Food and Agriculture Organization of the United Nations (2005). “Forest products annual market review 2004-2005,” *United Nations* Geneva, Switzerland.

Buell, T. W., and Saadatmanesh, H. (2005). “Strengthening timber bridge beams using carbon fiber,” *J. Struct. Eng.* 131(1), 173-187. DOI: 10.1061/(ASCE)0733-9445(2005)131:1(173)

Bal, B. C. (2014). "Flexural properties, bonding performance and splitting strength of LVL reinforced with woven glass fiber," *Constr. Build. Mater.* 51, 9-14. DOI: 10.1016/j.conbuildmat.2013.10.041

GB/T 20241-2006 (2006). "Laminated veneer lumber," China Standards Press, Beijing, China.

Haller, P., Heiduschke, A., Putzger, R., and Hartig, J. (2015). "Compressed laminated wood for the strengthening of glued laminated timber," *Bautechnik* 92(1), 28-35. DOI: 10.1002/bate.201400085

Hu, Y. C., Li, J., Cheng, F. C., and Zhang, X. J. (2010). "Design and analysis of the metal mesh reinforced LVL," *Adv. Mat. Res.* 113-116, 2145-2149. DOI: 10.4028/www.scientific.net/AMR.113-116.2145

Kim, Y. J., and Harries, K. A. (2010). "Modeling of timber beams strengthened with various CFRP composites," *Eng. Struc.* 32(10), 3225-3234. DOI: 10.1016/j.engstruct.2010.06.011

Laufenberg, T. L. (1983). "Parallel-laminated veneer: Processing and performance research review," *Forest Prod. J.* 33(9), 21-28.

Laufenberg, T. L., Rowlands, R. E., and Krueger, G. P. (1984). "Economic feasibility of synthetic fiber reinforced laminated veneer lumber (LVL)," *Forest Prod. J.* 34(4), 15-22.

Li, W. D., Zhang, Y., Ruan, Z. J., and Liu, Y. P. (2010). "Influence of poplar veneer compression and impregnation on properties of poplar plywood," *China Forest Prod. Ind.* 37(6), 10-13.

Liu, H. R., Liu, J. L., and Chai, Y. B. (2007). "Effect of the amount of resin impregnation on the properties of poplar LVL," *China Wood Ind.* 21(3), 11-13.

Liu, H. R., Liu, J. L., Li, L. Z., and Chai, Y. B. (2009). "Manufacture technology of dense poplar laminated veneer lumber," *China Forest Products Industry* 36(6), 13-16.

Mei, C. T., and Zhou, D. G. (2009). "Study on glass fiber reinforced poplar plywood used for concrete form," *China Forest. Sci. Technol.* 23(6), 79-82.

Pirvu, A., Gardner, D. J., and Lopez-Anido, R. (2004). "Carbon fiber-vinyl ester composite reinforcement of wood using the VARTM/SCRIMP fabrication process," *Compos. Part A-Appl. S.* 35(11), 1257-1265. DOI: 10.1016/j.compositesa.2004.04.003

Raftery, G. M., and Harte, A. M. (2011). "Low-grade glued laminated timber reinforced with FRP plate," *Compos. Part B-Eng.* 42(4), 724-735. DOI: 10.1016/j.compositesb.2011.01.029

Sasaki, H. (2001). "Lumber: Laminated veneer," in: *Encyclopedia of Materials: Science and Technology* (Second edition), Springer, The Netherlands, pp. 4678-4680. DOI: 10.1016/B0-08-043152-6/00815-9

Shen, G. L., and Hu, G. K. (2006). *Mechanics of composite materials*, Tsinghua University Press, Beijing (in Chinese).

Tenorio, C., Moya, R., and Munoz, F. (2011). "Comparative study on physical and mechanical properties of laminated veneer lumber and plywood panels made of wood from fast-growing *Gmelina arborea* trees," *J. Wood Sci.* 57(2), 134-139. DOI: 10.1007/s10086-010-1149-7

Wang, B. J., and Dai, C. (2005). "Hot-pressing stress graded aspen veneer for laminated veneer lumber (LVL)," *Holzforschung* 59(1), 10-17. DOI: 10.1515/HF.2005.002

Wang, Z. Q., Lu, X. N., and Huang, X. J. (2011). "Reinforcement of laminated veneer lumber with ramie fiber," *Adv. Mat. Res.* 332-334, 41-44. DOI: 10.4028/www.scientific.net/AMR.332-334.41

Wei, P. X., and Zhou, D. G. (2012). "Prospect and application of wood-based panels for electromechanical packaging," *China Forest. Sci. Technol.* 26(1), 13-16. DOI: 10.3969 /j.issn.1000-8101.2012.01.004

Wei, P. X., Wang, B. J., Zhou, D. G., and Dai, C. P. (2013). "Mechanical properties of poplar laminated veneer lumber modified by carbon fiber reinforced by polymer," *BioResources* 8(4), 4883-4898. DOI: 10.15376/biores.8.4.4883-4898

Xu, J. D. (2014). "The 8th forest resources inventory results and analysis in China," *Forestry Economics* 3, 6-8. DOI: 10.13843/j.cnki.lyjj.2014.03.002

Zhang, L., and Hu, Y. C. (2010). "Correlation analysis between dynamic Young's modulus and static MOE of the poplar LVL reinforced with multilayer fiberglass mesh," *Appl. Mech. Mater.* 26-28, 936-939. DOI: 10.4028/www.scientific.net/AMM.26-28.936

Zhang, X. C., Zhu, Y. D., Yao, C. Q., Li, Y. J., and Zhang, Q. S. (2012). "Influence of hot-pressing press and board density on compression strength of bamboo-wood composite laminated veneer lumber," *J. Bamboo Res.* 31(3), 23-27.

Zhou, A., Tam, L., Yu, Z., and Lau, D. (2015). "Effect of moisture on the mechanical properties of CFRP-wood composite: An experimental and atomistic investigation," *Compos. Part B-Eng.* 71, 63-73. DOI: 10.1016/j.compositesb.2014.10.051

Zhu, Y. X., Guan, M. J., and Zhang, X. D. (2005). "Studies on impact performance of bamboo strengthened laminated veneer lumber of poplar," *J. Nanjing Forest. Uni.* 29(6), 99-102.

Article submitted: July 7, 2015; Peer review completed: July 24, 2015; Revised version received and accepted: August 13, 2015; Published: September 18, 2015.
DOI: 10.15376/biores.10.4.7455-7465