Mechanical Properties of Poplar Laminated Veneer Lumber Modified by Carbon Fiber Reinforced Polymer

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Poplar (*Populus euramericana* cv.) is one of the most important fast-growing tree species in China, but so far its utilization has been limited to nonstructural wood-based panels. The objective of this work was to develop a good understanding of how to improve the mechanical properties of poplar laminated veneer lumber (LVL) with carbon fiber reinforced polymer (CFRP). A theoretical model was successfully developed to predict the bending modulus of elasticity (MOE) of LVL reinforced by CFRP. To validate the model, two different configurations of LVL were made in the laboratory: LVL reinforced with a single layer of CFRP on one side (LVL-SR) and LVL reinforced with a single layer of CFRP on each side (LVL-DR). It was found that the model prediction of the LVL MOE agreed well with the experimental results. LVL reinforced with CFRP had a greater MOE and modulus of rupture (MOR) than the control LVL. The MOE of the LVL-SR and LVL-DR increased by 40% and 67%, respectively.

Keywords: Laminated veneer lumber (LVL); Modulus of elasticity (MOE); Modulus of rupture (MOR); Carbon fiber reinforced polymer (CFRP); Poplar; Configuration

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INTRODUCTION

Poplar (*Populus euramericana* cv.) is one of the most important fast-growing species in 30 years of plantation history in China. However, due to its low density, poplar has seldom been used for structural applications (Ding 2005). It has typically been used as a raw material for medium density fiber board (MDF), particle board, and nonstructural plywood (Zhang *et al*. 2005; Liu *et al*. 2007; Li *et al*. 2011).

Engineered wood products (EWPs) include glued-laminated timber (Glulam), oriented strand lumber (OSL), parallel strand lumber (PSL), oriented strand board (OSB), and laminated veneer lumber (LVL) (Lam 2001). The advantages of these materials are more uniform physical and mechanical properties compared with solid wood because of their reconstitution and densification (Burdurlu *et al.* 2007; Ribeiro *et al*. 2009; Kılıç 2011).

LVL is made by laminating multi-layers of veneers in the longitudinal direction. It has been widely used in construction and heavy packaging in developed countries (Wei and Zhou 2012). In China, poplar has been used to manufacture LVL for about 10 years. However, its application has been limited to nonstructural uses such as floor and furniture components (Liu *et al*. 2007; Li *et al*. 2011). Due to its weak mechanical properties, poplar LVL is difficult to use in electromechanical packaging and residential building (Ding 2005; Wei and Zhou 2012). New technologies are needed to manufacture high performance LVL from low-quality and fast-growing poplar.

Over the years, LVL reinforcement methods have been developed, including veneer densification (Inoue *et al*. 2008; Bekhta *et al.* 2012; Buyuksari 2012); veneer impregnated with polymer (Laks *et al*. 1988; Dimri and Shukal 1991; Dimri *et al*. 1992; Hashim *et al*. 1992; Laks and Manning 1995; Yalinkilic *et al*. 1999); mixing high-density hardwood and bamboo (Wong *et al.* 1996; Wang *et al.* 2005; Xue and Hu 2012); and fiber reinforcing materials (Laufenberg *et al.* 1984; Martin *et al.* 2000). The fiber reinforcing materials technology has been applied to a wide range of timber and glulam but not LVL.

To reinforce glulam, materials explored over the past few decades include aluminum; bulk or wire steel; glass fibers; ceramic fibers; and natural and synthetic fibers (Spaun 1981; Bulleit 1984; Anca *et al.* 2004; Zhang *et al.* 2011). Use of synthetic materials to reinforce wood has been reported in numerous research papers dating back to the early 1960s. Fiber reinforced polymers (FRPs) are composites formed from the linking of fibers to an adhesive matrix. The fibers are responsible for the strength of the composites, while the adhesive is responsible for the stress transmission (Fiorelli and Dias 2011). However, it has not been cost-effective to implement this technology for commodity products due to the high cost of fiber reinforcements. Currently, the changing market is characterized by the lower supply and higher cost of top-grade natural wood. In the meantime, the price of synthetic fibers is decreasing due to the rapid development of the petro-chemical industry. Those changes provide opportunities for FRPs to enhance LVL or other EWPs (Laufenberg *et al*. 1984; Tingley 1996).

Many researchers have studied the effects of glass fibers or carbon fibers on the tension of glulam in terms of its bending failure (Rowlands *et al*. 1986; Triantafillou and Deskovic 1991; Plevris and Triantafillou 1992; Tingley 1996; Dagher *et al*. 1996, 1998; Yang and Liu 2007; Zhuo 2009; Wang *et al.* 2010). The core layer has no significant effect on the flexural properties of LVL (Meekum 2010). Due to different configurations of LVL reinforced by glass fiber, the resulting modulus of elasticity (MOE) and modulus of rupture (MOR) are dramatically different. Thus, an optimal design of LVL lay-up is needed to take full advantage of the reinforcement. In general, positioning the glass fiber closer to the surface veneer layer yields better reinforcement (Mei and Zhou 2009). FRPs offer good corrosion resistance and have a high strength to weight ratio. When compared with the control glulam, increases in the load-carrying capacity of 44 to 63% and stiffness of 10% were achieved with FRPs (Dagher *et al*. 1996, 1998; Buell and Saadatmanesh 2005; Johnsson *et al*. 2006). In addition, laminated wood reinforced with horizontal and vertical pultruded materials exhibits a higher MOR than solid wood or controls. Compared to laminated wood with vertically pultruded materials, the horizontal solution is satisfactory, as it uses only one layer of composite to yield the same MOR of laminated wood with two layers of vertical composites (Ribeiro *et al*. 2009). As a result, reinforcing with FRPs has emerged as a new solution that permits the use of low-grade wood for high-performance glulam or LVL manufacturing.

To date, research has focused on the use of aramid, carbon, and glass fibers as FRP reinforcement (Dorey and Cheng 1996). Aramid fiber is sensitive to moisture content (MC), making it less suitable for reinforced timber (Johnsson *et al.* 2006). Although carbon fibers have similar or higher cost than glass fibers, carbon fiber reinforced polymer (CFRP) provides improved stiffness and strength properties with a lower weight, which is more suitable for reinforcing glulam beams (Anca *et al.* 2004). Moreover, CFRP is compatible with wood in relation to its mechanical properties. For example, wood begins to lose its strength at 150 °C, and the temperature resistance of CFRP is greater than 150 °C (Issa and Kmeid 2005).

Structural epoxy adhesive remains the first choice to form a FRP-wood bond because of its gap-filling properties, limited shrinkage in curing and low required clamping pressure. Consequently, epoxy adhesives are commonly selected for bonding applications in rods and bars for upgrading or repairing timber members (Raftery *et al.* 2009a, b).

Most of the reinforcement solutions with fibers have been on the tensile surface only (Tingley 1996; Yang and Liu 2007; Zhuo 2009; Wang *et al.* 2010). However, use of a layer of FRP at the bottom of the product could cause difficulties in releasing during fabrication and subsequent maintenance in service. By comparison, with wood as the outermost lamination and the FRP as the sub-layer, a good protection to the FRP layer is warranted and the nail-holding capacity, impact, and slip resistance of the product is largely improved (Stevens and Criner 2000). Although many scientists have investigated FRP reinforced glulam, fiber reinforcing LVL has not been widely reported. In addition, studies concerning the strengthening effect of the FRP with symmetrical lay-up in the tension and compression regions have seldom been conducted (Hernandez *et al.* 1997; Ogawa 2000).

The objectives of this work were as follows: 1) to develop a model to predict the bending MOE of CFRP enhanced poplar LVL; and 2) to experimentally examine the effect of CFRP reinforcement on LVL bending performance.

MODELING OF BENDING MOE OF CFRP REINFORCED LVL

Wood is an anistropic material. However, it can be further described as an orthotropic material with unique and independent mechanical properties in the longitudinal, radial, and tangential directions (Ribeiro *et al.* 2009). Due to its unidirectional structure, LVL also has orthotropic characteristics. This work mainly examined the bending performance of small beams with the length of the beams parallel to the grain direction. It was assumed that the CFRP reinforced LVL was composed of two parts: one being the LVL with homogenous properties in the longitudinal direction, and the other being CFRP with unidirectional fibers.

In this work, a bending beam with a uniform load was analyzed to determine the suitable layer where the reinforcements should be placed first, and the neutral axis position of CFRP reinforcing LVL on one side was calculated. Finally, the final MOE model was developed based on the discussion on the effect of compression and resin.

Mechanical Analysis of Bending Beam

The bending configuration of a LVL beam with a uniform load is shown in Fig. 1.

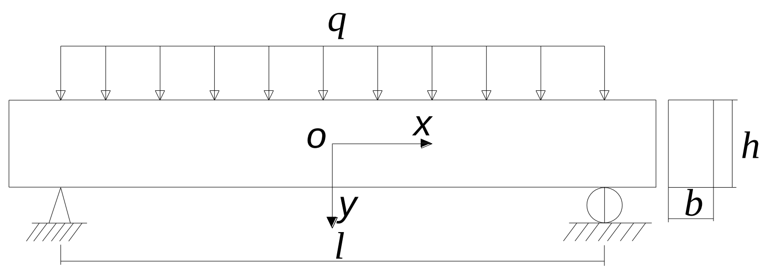

Fig. 1. LVL beam: L—length of beam (mm), h—height of beam (mm), b—width of beam (mm). (x—parallel to span direction, y—direction of height of beam)

To simplify calculation, unit beam width ($b = 1$) is assumed. According to the classic theory of elastic mechanics (Xu 2002), normal stress, σ_x and σ_y, and shear stress, τ_{xy}, are given as follows,

$$\begin{cases} \sigma_x = \frac{M}{I} y + q\frac{y}{h}(4\frac{y^2}{h^2} - \frac{3}{5}) \\ \sigma_y = -\frac{q}{2}(1+\frac{y}{h})(1-\frac{2y}{h})^2 \\ \tau_{xy} = \frac{F_S S}{bI} \end{cases} \tag{1}$$

where M is the bending moment, given by $\frac{ql}{2}\left(\frac{l}{2}+x\right) - \frac{q}{2}\left(\frac{l}{2}+x\right)^2$, F_S is the shear force, given by $-qx$, I is the moment of inertia, given by $\frac{1}{12}h^3$, S is the static moment, given by $\frac{bh^2}{8} - \frac{by^2}{2}$, and q is the load per unit length.

In this work, the span to height ratio, namely, l/h was over 4, so σ_x was approximately equal to $\frac{M}{I}y$. During lateral bending, the bending moment of the beam changes with the position of the cross section. Normally, the maximum normal stress, σ_{xmax}, takes place on the outermost layer from the neutral axis ($x = 0, y = \pm h/2$),

$$\sigma_{xmax} = \frac{M_{max} y_{max}}{I} = \frac{3ql^2}{4h^2} > 12q \tag{2}$$

where M_{max} is the maximum bending moment and y_{max} is the maximum displacement.

When y is equal to $-\frac{h}{2}$, the maximum stress value of σ_y is q. Because of $\sigma_{ymax} \ll \sigma_{xmax}$, σ_y can be neglected. The $x-y$ plane shear stress, τ_{xy}, has its maximum value $\frac{3}{2}\frac{F_S}{bh}$ at the neutral axis.

According to the analysis above, the failure would most likely happen on the face layers, so this is where the reinforcements should be placed.

Reinforcement of CFRP

As shown in Fig. 2, a single layer of CFRP reinforcing LVL on one side (LVL-SR) results in a shift of the neutral axis position to the lower part.

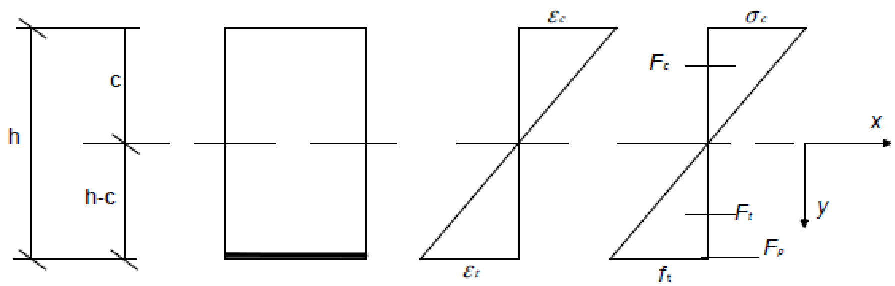

Fig. 2. Bending stress-strain analysis of LVL-SR

Taking the geometric relation into account leads to,

$$\frac{c}{h-c} = \frac{\varepsilon_c}{\varepsilon_t} \tag{3}$$

where c is the height of the compressed region, ε_c is the strain of the compression region, and ε_t is the strain of the tension region.

The stress and strain relationship is expressed as,

$$\sigma_c = E_L\varepsilon_c = E_L \frac{c}{h-c}\varepsilon_t \tag{4}$$

where σ_c is the compression stress and E_L is the MOE of LVL.

A perfect bond between CRFP and wood veneer would yield an equal strain ε_t. Thus, the load on the cross sectional area of CFRP, F_P, is defined as,

$$F_P = A_P\sigma_P = bh\,\beta\alpha_E E_L\varepsilon_t \tag{5}$$

where $\alpha_E = \frac{E_P}{E_L}$; $\beta = \frac{A_P}{bh}$; E_P is the MOE of CFRP, A_P is the cross-sectional area of CFRP, and σ_P is the tension stress of CFRP layer.

On the whole cross-sectional area of the beam, the two parts' forces are equal and opposite,

$$F_t + F_P = F_c \tag{6a}$$

$$F_c = \frac{1}{2}\sigma_c bc \tag{6b}$$

$$F_t = \frac{1}{2}f_t b(\mathrm{h}-c) = \frac{1}{2}E_L\varepsilon_t b(\mathrm{h}-c) \tag{6c}$$

where F_t is the tensile force of the LVL part, F_c is the compression force of the whole beam, and f_t is the tension stress of the LVL part.

The height of the compressed region, c, is eventually obtained as follows:

$$c = \frac{1+2\beta\alpha_E}{2(1+\beta\alpha_E)}h \tag{7}$$

Due to the thinness of the CFRP layer, its effect on the total thickness of the beam can be neglected, so the total and each component's moment of inertia of LVL, I, I_L and I_P, are given by,

$$I = I_L = \int_{-c}^{h-c} by^2\, dy \tag{8a}$$

$$I_P = \int_{h-c-h_0-\beta h}^{h-c-h_0} by^2 dy \tag{8b}$$

where h_0 is the thickness of veneer, $\frac{A_P}{b}$ (or βh) is the thickness of CFRP, I_L is the moment of inertia of the LVL component, and I_P is the moment of inertia of the CFRP component.

According to the theory of laminated beams in pure flexure, the overall stiffness, $E_t I$, is equal to the sum of the components' stiffness (Shen and Hu 2006; Ribeiro *et al*. 2009), or:

$$E_t = \frac{E_L I_L + E_P I_P}{I} = E_L + E_P \frac{\int_{h-c-h_0-\beta h}^{h-c-h_0} y^2 dy}{\int_{-c}^{h-c} y^2 dy} \tag{9}$$

Effect of Compression and Resin

It is known that moisture content (MC) affects the physical and mechanical properties of wood (Silva *et al.* 2012), but the effect of MC on the mechanical properties of wood can be downplayed when the change of MC is small. Assuming that each layer of resinated veneer has the same compression ratio (CR) as LVL, the tensile MOE of LVL is approximately equal to that of each layer of resinated veneer. According to composites mechanics (Shen and Hu 2006), the MOE of each resinated veneer, E, is given by (Lu *et al*. 2002),

$$E = v_f E_f + v_g E_g \tag{10}$$

where E_f is the tensile MOE of the wood veneer cell wall (E_f for poplar is 18,000 MPa), v_f is the volume fraction of the veneer cell wall, E_g is the MOE of the glue solids (E_g for phenol-formaldehyde (PF) is 8,800 MPa), and v_g is the volume fraction of the glue solids.

Based on a newly modified mechanics theory for wood composites (Lu *et al.* 2002), E can be further defined by,

$$E = E_v^e + E_g^e = \frac{\rho_0}{\rho_f(1-CR)} E_f + \frac{G_s}{t_0(1-CR)\rho_g} E_g \tag{11}$$

where E_v^e is the equivalent MOE of wood veneer, E_g^e is the equivalent MOE of glue solids, ρ_f is the density of the cell wall (ρ_f for poplar is 1,500 kg/m^3), CR is the compression ratio of resinated veneer, which is given by $\frac{t_0-t}{t_0}$ (t_0 represents the initial thickness of veneer, and t is the final thickness of veneer), G_s is the glue solids spread level of veneer, and ρ_g is the density of the glue solids, which is 1,500 kg/m^3 for phenol-formaldehyde.

Given that ρ_0, G_s , and t_0 are known (here, ρ_0= 400 kg/m^3; G_s= 110 g/m^2; and t_0= 1.9 mm), the relationship between the MOE of resinated veneer and CR can be shown as in Fig. 3.

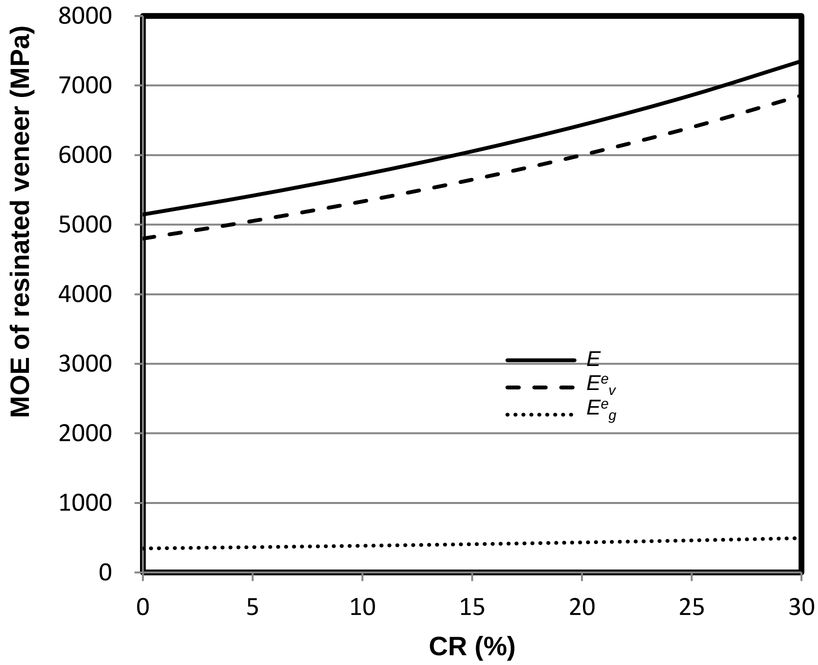

Fig. 3. The relationship between the MOE of resinated veneer and CR

With increasing CR, the MOEs of resinated veneer and the equivalent MOE of wood veneer increases dramatically, but the equivalent MOE of glue solids increases very little. The contribution of the glue is significant only in plywood made up of veneers of thickness less than 1.20 mm (Okuma 1976; Booth and Hettiarachchi 1990). In fact, in this case, the contribution of glue to the MOE is about 6.7%, so the MOE of resinated veneer mainly depends on wood veneer.

In this work, the thickness of the selected veneer was 1.9 mm. Consequently, the effect of glue was negligible in the model. The stiffness and strength of LVL are mainly contributed by the cellulose content of veneer, or the MOE of wood cell wall (Xue and Hu 2012). Assuming that each layer of veneer in the LVL assembly has the identical MOE and thickness (or volume), equation (11) becomes,

$$E_L = E = \frac{\rho_0}{\rho_f(1-CR)} E_f \tag{12}$$

where E_L is the longitudinal MOE of LVL after hot pressing and E is the MOE of each veneer. Thus, the final MOE can be derived from equation (9).

$$E_t = \frac{\rho_0}{\rho_f(1-CR)} E_f + \frac{E_P \int_{h-c-h_0-\beta h}^{h-c-h_0} y^2 dy}{\int_{-c}^{h-c} y^2 dy} \tag{13}$$

If LVL is reinforced with double CFRP in the symmetrical tensile and compression regions, the position of the neutral axis does not change, and the calculation of E takes the following form,

$$E_t = \frac{\rho_0}{\rho_f(1-CR)} E_f + 2\frac{E_P \int_{\frac{h}{2}-h_0-\beta h}^{\frac{h}{2}-h_0} y^2 dy}{\int_{-\frac{h}{2}}^{\frac{h}{2}} y^2 dy} \tag{14}$$

When thickness control is used to press the LVL assembly, the LVL reinforced by CFRP has a greater CR due to the addition of the CFRP layer.

EXPERIMENTAL

Materials

To minimize the natural material variability, poplar trees of the same age were harvested from the same region of Linyi in China and then cut into blocks. Veneers with thicknesses of 1.9 mm were peeled at a mill and carefully selected to be free from knots and damage. Subsequently, veneers were cut into smaller sheets with dimensions of 60 mm × 60 mm × 1.9 mm (length × width × thickness). Afterwards, veneer sheets were dried to a target MC of 6 to 8%. They were further sorted by density with a range from 350 kg/m^3 to 450 kg/m^3.

Two types of adhesives were used in this work. One was commercial phenol-formaldehyde (PF) resin with a solids content of 48%. The spread rate was 224 g/m^2 (double glue lines) for veneer-to-veneer bonding. The other was epoxy adhesive film with a thickness of 0.1 mm, used in the CFRP-veneer interface. The curing time was 90 min at a temperature of 140 °C. The identical curing temperature of these two resins helps ease the LVL manufacturing.

CFRP selected in this work was a carbon fiber prepreg in which unidirectional carbon fibers are impregnated in an epoxy resin matrix to form an intermediate composite. The tensile strength, MOE and compression strength of CFRP were 1600 MPa, 112 GPa, and 1000 MPa, respectively, and the thickness of CFRP was 0.16 mm.

LVL Lay-up

Two configurations of LVL reinforced with CFRP were made: one was a single layer of CFRP between the surface layer and sub-layer on one side (LVL-SR); and the other was a single layer of CFRP between the surface layer and sub-layer on each side (LVL-DR). As shown in Fig. 4, two different configurations of LVL were made in the laboratory: LVL-SR and LVL-DR.

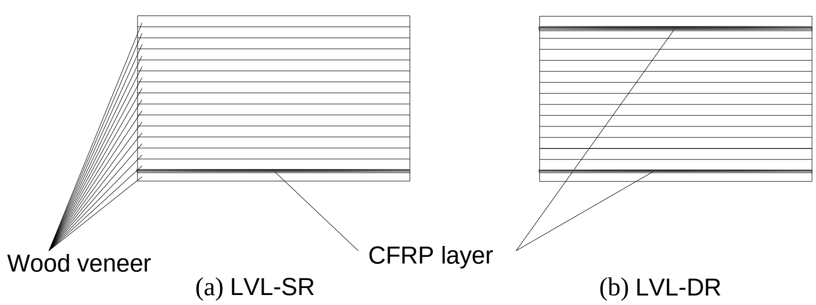

Fig. 4. Two configurations of LVL reinforcement: (a) LVL-SR; (b) LVL-DR

After spreading the glue, 15 wood veneer sheets and CFRP layers were laminated parallel to the grain direction and then cold pressed for 30 min, followed by hot pressing for about 90 min. A control LVL was also made for comparison. Three replicates were used generally, yielding a total of 9 LVL billets. These were cut into bending specimens (600 mm × 40 mm × 25 mm) with 9 from each billet after one week of storage. All test specimens were placed in a climate chamber at a temperature of 20±2 °C and a relative humidity (RH) of 65% until the specimen weights remained constant. Then, flat-wise bending tests were carried out in a four-point loading scheme, according to the Chinese National Standard GB/T20241-2006, as seen in Fig. 5.

Fig. 5. Testing of an LVL beam

RESULTS AND DISCUSSION

Using the control as input for estimating the veneer MOE, the LVL-SR and LVL-DR MOEs were calculated using equations (13) and (14). Table 1 summarizes the comparison of measured and predicted MOE data.

Table 1. Comparison of Measured MOEs and Predicted MOEs

Series	Density (kg/m^3)	CR	Measured MOE (MPa)			Predicted MOE (MPa)	Reinforcement ratio
			Mean	Std. dev	CV		
Control LVL	520	12.3%	8142.5	988.0	12.1%	-	1.00
LVL-SR	530	13.8%	11384.6	517.5	4.6%	11370.9	1.40
LVL-DR	540	14.4%	13629.6	864.4	6.3%	13689.9	1.67

Increasing CR could improve the stiffness of LVL. According to Wang and Dai (2005), every 1% increase in CR (lower than 10%) results in an approximately 1% increase in aspen LVL stiffness. The relationship between LVL MOE and compression ratio (CR) was described as equation (12).

The addition of CFRP significantly increased the final product MOE. The LVL-SR had a 40% greater MOE than the control LVL. By comparison, the LVL-DR had a 67% greater MOE. Table 1 also shows that the model predictions were very accurate compared to the experimental data, with prediction errors of only 0.12% and 0.44%, respectively.

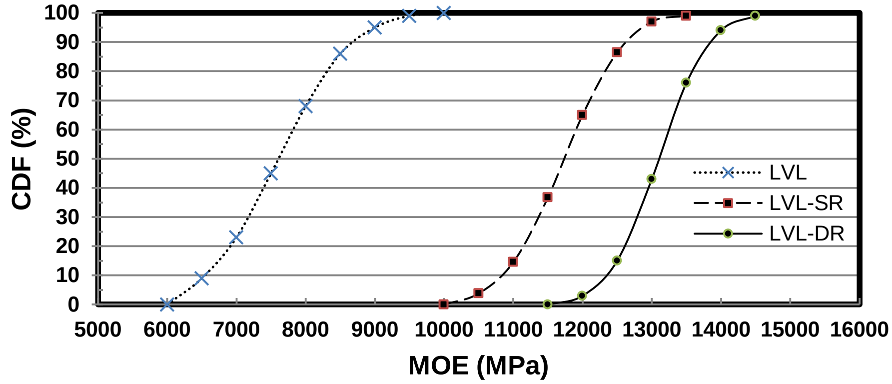

Fig. 6. CDF of bending MOE of the three LVL configurations

Figure 6 shows the cumulative distribution function (CDF) of the bending MOE of two configurations of LVL with reinforcement compared to the control LVL. The MOE of the control LVL had a greater variation than the other two configurations. The LVL-SR and LVL-DR test data had no overlap. The introduction of reinforcement resulted in a reduction in the variation of MOE.

Figure 7 shows the bending MOR of the three LVL configurations (error bar: LVL: ±8.1 MPa; LVL-SR: ±6.8 MPa; LVL-DR: 12.4 MPa). It was obvious that the LVL-SR had the highest bending strength. It was very interesting to note that the MOR of LVL-DR was less than that of LVL-SR. The introduction of one CFRP layer did not result in a significant change in the variation, but reinforcements on both sides significantly increased the variation. The double reinforcement reduced the load-carrying capacity of the LVL because the properties of the two materials differed from each other greatly, a fact that will be discussed in detail later in this paper.

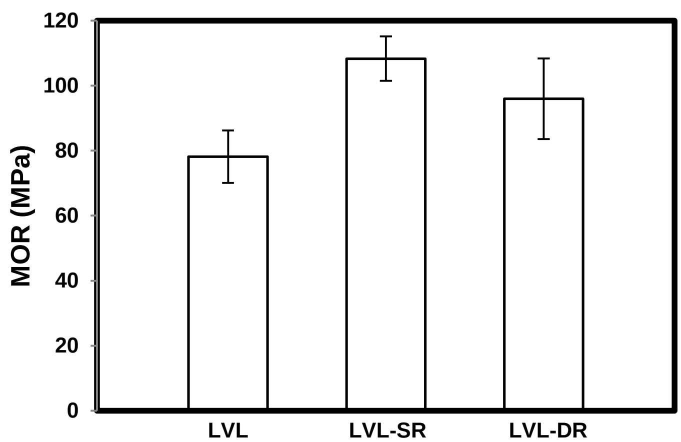

Fig. 7. Bending MOR of the three LVL configurations

Figure 8 shows the failure modes of the three LVL configurations. The outermost bottom veneer layer of the control LVL failed during maximum load tension. However, for the LVL-SR, the failure of the outermost veneer layer occurred first, followed by failure of the veneer sub-layer and failure of CFRP in most cases. For LVL-DR, an interesting phenomenon was that compression wrinkling was first observed in the top lamina (top surface veneer layer and CFRP), but the load still went up until delamination between the bottom layer and sub-layer occurred. This phenomenon was also reported in previous studies with respect to FRP reinforced glulam, but it was not carefully explained (Yang and Liu 2007; Hernandez *et al*. 1997). By comparison, the LVL-SR had a higher load-carrying capacity than the LVL-DR.

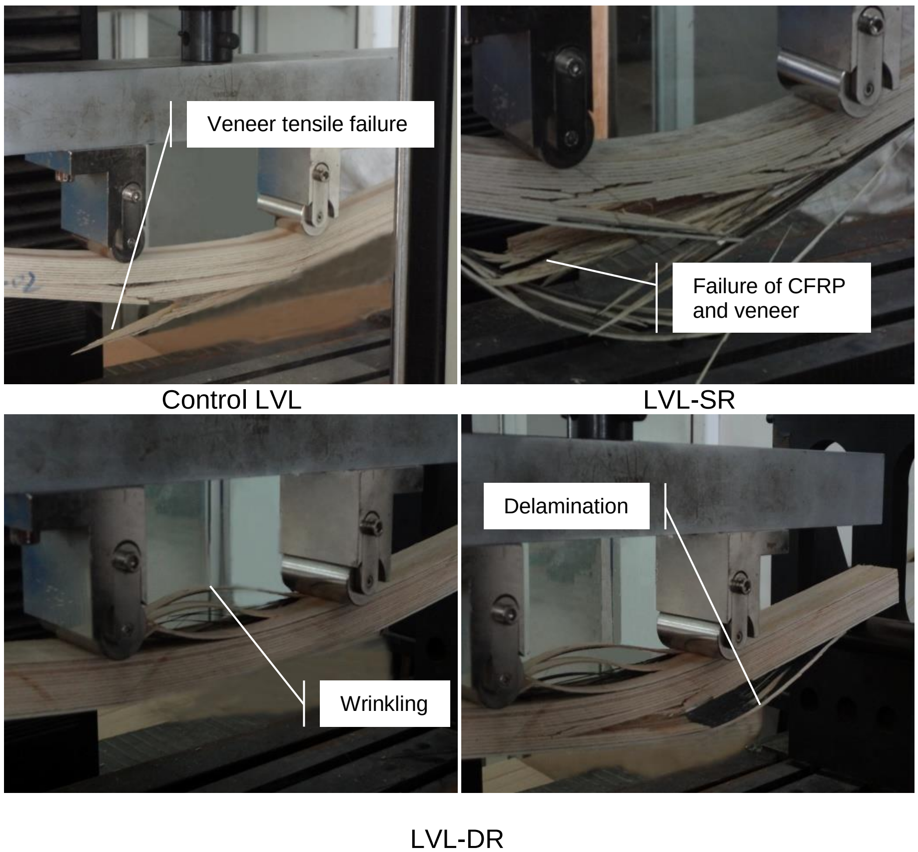

Fig. 8. Failure modes of the three LVL configurations

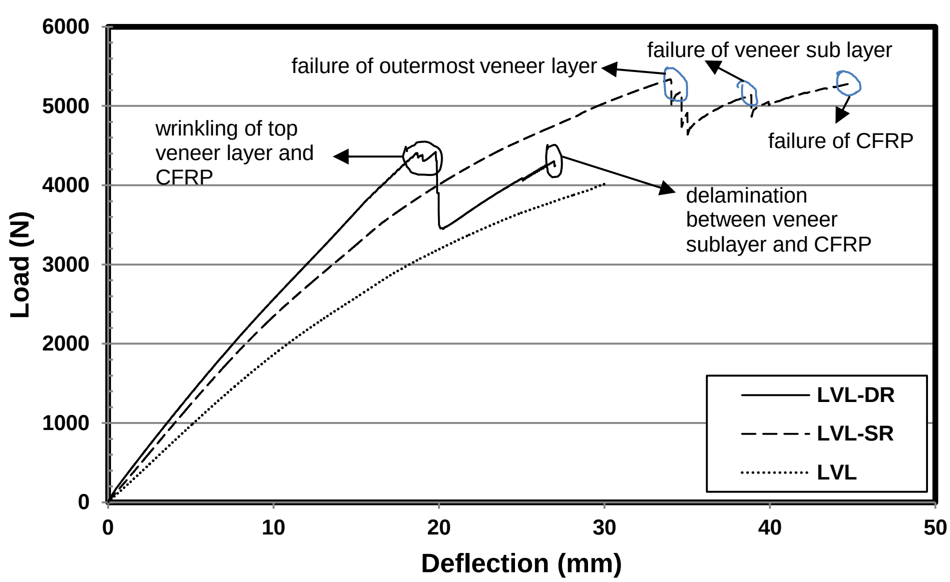

Fig. 9. Load versus deflection curves for LVL, LVL-SR, and LVL-DR

Generally, the matrix resin carries the primary compression load when a carbon-reinforced composite is compressed. The MOE of epoxy resin is about ten times that of wood, so according to Hooke's law, the CFRP has greater compression stress than wood veneer. Note that wood and CFRP adjacent to the interface had the same strains. When the CFRP's compression stress was larger than the bonding strength between the CFRP and wood, the top CFRP layer began to delaminate from the matrix wood due to wrinkling and lost its reinforcing effect. However, the stress of the beam redistributed and the neutral axis moved down. The effective cross-section of the LVL-DR thus decreased, and the load-carrying capacity declined.

Figure 9 presents the load versus deflection curves obtained for the control LVL, LVL-SR, and LVL-DR. The control LVL did not show a yield stage. This could be due to the fact that the tensile strength of wood is larger than its compression strength. When the LVL beam is bent, the compressed region enters plastic deformation while the tensile region always undergoes elastic deformation. With the load maximized, the bottom layer of veneer then broke.

The LVL-SR load versus deflection curve showed that there was a yield stage. In the testing of LVL-SR, the bottom veneer layer failed first, so the curve dropped suddenly as the load went up, until the sub-layer broke. Although the tensile strength of carbon fiber was much higher than that of wood veneer, the adjacent veneer broke, and soon afterwards, the splintering caused the CFRP layer to fail. LVL reinforced with two CFRP layers had a smaller load-carrying capacity, with the top CFRP layer in the compression region not functioning very well. This could be the main reason why many previous studies only focused on reinforcement in the tension zone of the glulam beam.

Overall, the results demonstrated that CFRP can be used to produce stronger LVL from poplar.

CONCLUSIONS

1. This work developed a model to predict the bending modulus of elasticity (MOE) of laminated veneer lumber (LVL) reinforced by carbon fiber reinforced polymer (CFRP). Compared with the measured results, the model accurately predicted the MOE of poplar LVL modified by CFRP.
2. The experimental results revealed that LVL reinforced by thin carbon fiber material had a greater bending MOE and modulus of rupture (MOR) than the control LVL. Use of CFRP to reinforce poplar LVL is feasible.
3. The additional CFRP reinforcement did not result in an equivalent increase in the MOE. The LVL-SR (one-side reinforced) had a 40% greater MOE than the control LVL, and the LVL-DR (both sides) had a 67% greater MOE than the control LVL.
4. CFRP reinforcement on either one side or two sides exhibited different effects; the former had a higher MOR than the latter, both being higher than that of the control LVL. Compared to the LVL-SR, the additional CFRP of the LVL-DR reduced the load-carrying capacity. The reinforcement in the compression region did not function properly due to the wrinkling of the wood veneer and CFRP. Thus, it is more effective to place the CFRP on the tension side of the LVL.

5. The location of CFRP reinforcement in the LVL should be optimized. The solution is to place the reinforcement as close to the bottom surface layer as possible. However, considering that CFRP bonded to the wood surface may cause some problems in manufacturing and maintenance, it is recommended that CFRP be placed between the outermost veneer layer and the veneer sub-layer.

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