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Utilization of Chinese fast-growing trees and the effect of alternating lamination using mixed-species eucalyptus and poplar veneers

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Abstract

Over the past few decades, the sustainable forest area in China has increased remarkably, with 2400 million cubic meters of eucalyptus produced in 2018 in Guangxi which is the largest plantation area in China. In this study, the effect of alternating lamination using soft poplar veneers and hard eucalyptus veneers, on the mechanical properties of laminated veneer lumber (LVL), was examined. Eucalyptus and poplar veneers were imported from China to Japan to manufacture the LVL. For both eucalyptus and poplar veneers, the pith side (innerwood) sheets were lighter in density than the bark side (outerwood) sheets. The specific Young's modulus of alternating LVL with hard eucalyptus veneers and soft poplar veneers was smaller than that of the mono-species LVL of eucalyptus and poplar. Strain distributions were obtained with the compression test by using the digital image correlation method. Normal strains showed that the hard eucalyptus layer behaved as a thin plate, whereas the soft poplar layer mitigated the movement of the hard eucalyptus layer. Alternating lamination decreased the variation in the elastic modulus of LVL made from fast-growing species. Therefore, the soft layers mitigated the movement of the hard layers, which had large variations in mechanical properties.

Keywords: Fast-growing tree, Eucalyptus, Poplar, China, Alternating lamination, LVL

Introduction

The implementation of measures to protect natural forests is increasing worldwide to save biodiversity. Wood resources used to produce industrial products that were once obtained from natural forests are now being provided by plantation forests. Fast forestry can effectively produce wood resources in small areas over short time frames. Such forestry allows for short logging rotation cycles in plantation areas by using fast-growing species, such as eucalyptus, acacia, falcate, and poplar [1]. Over the past few decades, the forest area in China has increased remarkably, and fast forestry has made a significant contribution to the expansion of plantation forests [2]. Poplar and eucalyptus are attracting the attention as material of plywood and laminated veneer lumber (LVL) in the world [3–5]. Poplar in East China and eucalyptus in South China play an important role in developing the wood-based product industry of plywood, fiberboard, and paper [6]. After selective breeding of many poplar species was undertaken at Nanjing Forestry University and other research institutes, commercial poplar plantations of *Populus gigra* and *P. deltoides* began in the 1980s and the wood-based industry using poplar material developed in the 1990s. *Eucalyptus urophylla* and the hybrid of *E. urophylla* and *E. grandis* were found to grow fast in China from joint research with an Australian institute; therefore, eucalyptus plantations began in the 2000s, and the plantation area increased by 100 km^2 per year during the 2010s [7]. In Japan, 610,000 m^3 of log for plywood material was imported from China in 2007,

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which increased to 1,520,000 m^3 by 2017. The percentage of Chinese plywood among the total imported plywood changed from 10% in 2007 to 27% in 2017 [8]. In the statistical data published by the Japanese Government, plywood data consists of plywood and LVL. Chinese plywood is commonly used for packing industrial products and Chinese hardwood-LVL is used as non-bearing studs for house in Japan. Such plywood is a laminated veneer material used for building interior products and furniture because these require both smooth and hard surfaces and high dimensional stability.

However, planted trees in fast forestry areas mainly include juvenile wood, unlike the large trees in natural forests, and the mechanical properties of the timber vary considerably within the same log. This is because the planted tree is cut in the short-term, and fast forestry usually yields small logs for economic reasons. Chinese eucalyptus veneer is rarely glued to make LVL because adhesive failures frequently occur during the production process. However, alternating lamination using poplar and eucalyptus veneers improves this adhesive failure and variation in the mechanical properties of the eucalyptus LVL. In the present study, we aimed to investigate the effect of alternating lamination using soft veneer such as poplar and hard veneer such as eucalyptus on the mechanical properties of the LVL.

Materials and methods

Eucalyptus forestry in China and rotary lathe veneer of fast-growing trees

We visited Nangning, in the Guangxi province, and Lianyungang in the Jiangsu province of China, in September 2019 to study eucalyptus and poplar veneers. First, we visited the Guangxi Forest Industry Trade Association to collect information regarding the eucalyptus forestry in China. Next, we visited a eucalyptus veneer mill in Nangning and a poplar veneer mill in Lianyungang to obtain rotary lathe veneers (Fig. 1).

Fig. 1 Rotary lathe mill for the poplar veneer in Lianyungang, China (September 2019)

At the eucalyptus veneer mill, 1.3 m-length eucalyptus logs, which were 8 to 18 cm in diameter, were used for the rotary lathe material. The logs were lathed into a veneer, which was 1.6 mm in thickness, 630 mm in width, 1270 mm in fiber length, and approximately 35 mm in diameter (Fig. 2). At the poplar veneer mill 2.6 m-length poplar logs, 10 to 28 cm in diameter and cut to 1.3 m lengths, were lathed into a veneer which was 1.8 to 1.9 mm in thickness, 840 mm in width, and 1270 mm in fiber length. Defective veneers, with large holes and splits, were excluded from the study and the available veneers were dried outdoors for a couple of days.

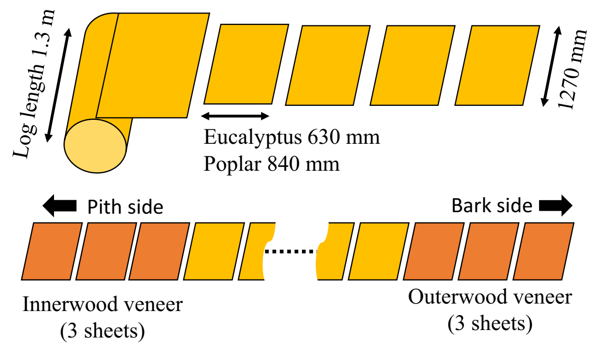

Fig. 2 Lathe process of eucalyptus and poplar log, and selection of innerwood veneer and outerwood veneer

Because plantation trees are cut in the short-term, juvenile wood accounts for a large portion of the logs produced by fast forestry. We had to use the mature part as well as the juvenile part of the trees to improve the yield percentage; however, the veneer thus produced might be of inadequate quality for use as an industrial material as it would possess large variations in density and mechanical properties. To evaluate the quality of the eucalyptus and poplar veneers, 192 sheets of veneer, made from four eucalyptus logs and four poplar logs, were selected. We picked 3 sheets on the pith side (innerwood) and 3 sheets on the bark side (outerwood) from a continuous lathe veneer for each log. A total of 192 sheets were cut, each having a width of 300 mm and a fiber length of 600 mm and weighed to obtain the density.

Manufacture of laminated veneer lumber (LVL) for interior materials

The selected eucalyptus and poplar veneers were imported from China to Japan and six types of 20-ply LVL were made: innerwood poplar LVL (Pi-LVL), outerwood poplar LVL (Po-LVL), innerwood eucalyptus LVL (Ei-LVL), outerwood eucalyptus LVL (Eo-LVL), innerwood poplar and outerwood eucalyptus mixed LVL (PiEo-LVL), and outerwood poplar and innerwood eucalyptus mixed LVL (PoEi-LVL). A total of 96 sheets belonging to each species were sorted in weight order and the 30 lightest (innerwood) and 30 heaviest (outerwood) sheets were selected from each species, except PoEi-LVL, to make five types of LVL. In case of PoEi-LVL, a total of 20 sheets of similar weight and density veneers were selected.

The veneer sheets were arranged to achieve an even weight for each LVL and the eucalyptus and poplar veneers were piled up alternately for the mixed-species LVL (PiEo-LVL and PoEi-LVL). Resorcinol resin adhesive (room temperature curable, Oshika Deernol No. D-40) was used to adhere to the veneers. The adhesive was mixed with 100 parts resin and 15 parts hardener. The spread of the adhesive was 250 g/m^2 and the pressing time was 24 h under 1 MPa pressure and 10 °C. After pressing, the LVL boards were conditioned at 22.8 °C and 60% relative humidity for 2 weeks and cut into dimensions of 20 mm wide and 550 mm long. A total of 10 samples were made for each type of LVL. The thickness in the laminated direction was 40 mm for Pi-LVL and Po-LVL, 33 mm for Ei-LVL and Eo-LVL, and 37 mm for PiEo-LVL and PoEi-LVL.

Commercial Chinese LVL was also prepared to measure the strain distribution by using the compression test (Table 1). Thickness of veneer was different between poplar and eucalyptus in China. Number of ply in LVL made in this study is equal among poplar and eucalyptus to measure Young' s modulus in bending test. Commercial LVL was suitable to measure strain distribution because number of ply is different but thickness of LVL is equal. There were five pieces of mixed-species 17-ply LVL (PE-LVL), four pieces of eucalyptus 20-ply LVL (E-LVL), and five pieces of poplar 18-ply LVL (P-LVL). Density of E-LVL was close to that of PE-LVL. Eucalyptus veneer of PE-LVL might be difference form E-LVL in density because of commercial LVL. Each specimen was 60 mm in length and 30 mm × 30 mm in end. They were conditioned at 22.8 °C and 60% relative humidity for several days.

Table 1 Commercial LVL specimens used in the compression test (average)

Species	Poplar (P)	Eucalyptus (E)	Mixed (PE)
Density (kg/m^3)	576	619	631
Moisture content (%)	8.3	8.4	8.3

Measurement of the modulus of elasticity (MOE)

To evaluate the bending properties of the fast-growing tree LVL, specimens were tested in the edgewise direction using a universal testing machine (Augograph AG-I 100kN; Shimadzu, Kyoto, Japan). The specimens were supported at a span length of 500 mm and loaded at a 10 mm/min crosshead rate on the center of the specimen with a three-point bending test. Displacement–load diagrams were obtained from the displacement of the crosshead and force of the load cell. Bending strengths were measured using one specimen, and 20% of the breaking load estimated from the bending strength was loaded and the straight region of the diagram was obtained to calculate the MOE.

Strain distribution from the compression test parallel to the fiber direction

The aim of the present study was to understand the effect of alternating lamination, by using a soft veneer and hard veneer, on mechanical properties. To elucidate the deformation of the alternating laminated LVL, strain distributions on the surface were measured by a compression test using the digital image correlation (DIC) method. A random-dot pattern was sprayed with black ink on the observed surface of the specimen (Fig. 3). The specimens were compressed in the fiber direction within the elastic region by a universal testing machine (Augograph AG-I 100kN; Shimadzu, Kyoto, Japan) at a 0.5 mm/min crosshead rate (Fig. 4). Digital images of the surface were captured every 10 s; the system consisted of a cold light (LA-150TX; HAYASHI-REPIC, Tokyo, Japan), a digital camera (DMK23UP1300; Imaging Source, Bremen, Germany), and a macro zoom lens (LMZ50M; Kowa Optical Products, Nagoya, Japan). The images were analyzed using the original coding software of DIC to calculate the strain distributions [9, 10]. Square subsets for DIC analysis were placed on the images along each veneer layer to understand the movement of the veneers (Fig. 5). The

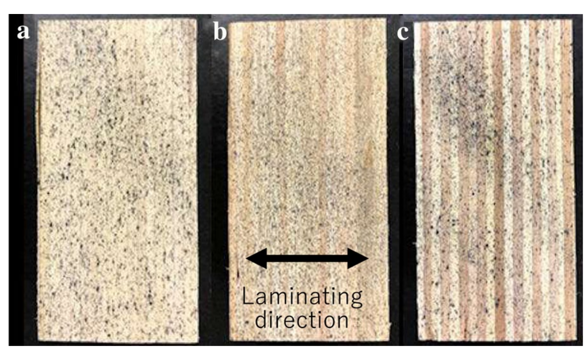

Fig. 3 Compression specimen: left: P-LVL, center: E-LVL, right: PE-LVL

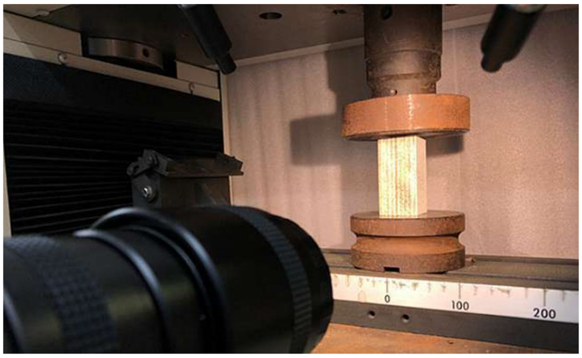

Fig. 4 Set-up for the compression test

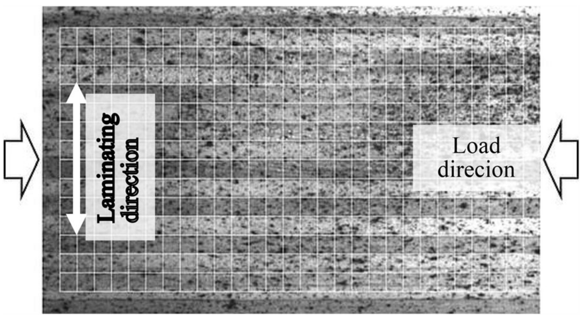

Fig. 5 Subsets for the digital image correlation analysis (white mesh on image of specimen)

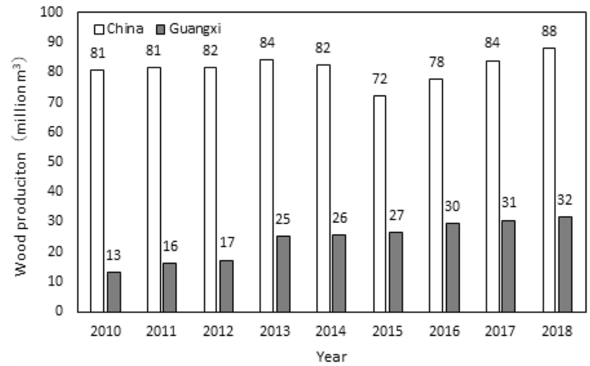

Fig. 6 Wood production in the plantation forests of China and Guangxi

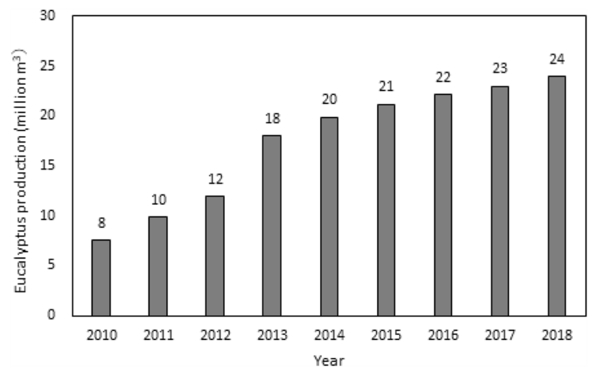

Fig. 7 Eucalyptus production in Guangxi

size of the subset was approximately equal to the thickness of the veneers and the obtained strains on the subsets were averaged for each veneer layer. We obtained the normal strain that was perpendicular and parallel to the laminating direction and shear strain on the edge surface.

Results and discussion

Eucalyptus forestry in China and rotary lathe veneer of fast-growing trees

The Guangxi Forest Products Industry Trade Association provided us with information regarding the eucalyptus plantations in this area. The forest area is 16 million ha, which covers 62.37% of the land area in Guangxi. The ratio is one-third of the domestic production in China. The plantation and eucalyptus forest areas are the largest in China, with approximately 6.6 million ha and 2 million ha, respectively. The commercial timber production in Guangxi has been increasing; in 2018, the production amount was 31.75 million cubic meters, which was 36% of China's total wood production (Fig. 6), approximately 24 million cubic meters of which was accounted for by eucalyptus wood (Fig. 7). Fast forestry has a rotation cycle of less than 10 years which enables efficient timber production. Both poplar and eucalyptus are sustainable resources.

Table 2 Density of veneer used to make LVL specimen (kg/m^3)

Veneer	Pi	Po	Ei	Eo
Mono-species LVL				
AVG	421	509	430	540
STD	15	13	14	46
Mixed-species LVL				
AVG	422	467	486	539
STD	15	11	12	45

AVG average value, *STD* standard diviation

The seleted veneer-sheet densities are shown in Table 2. Comparison between the densities of different species in mono-species LVL showed that poplar had a significantly lower density than eucalyptus ($p < 0.05$) in both innerwood and outerwood sheets, and within the same species the innerwood density was significantly lower than the outerwood density ($p < 0.05$) for both poplar and eucalyptus. For eucalyptus, the difference in density between the innerwood and outerwood was higher than poplar.

LVL density and MOE from the bending tests

The density and MOE of the LVL specimens are shown in Table 3. For both poplar and eucalyptus LVL, the density and MOE of innerwood LVL was significantly smaller than those of outerwood LVL ($p<0.05$). It was inferred that the density differences might have affected the MOE. The properties of the mixed LVL were in-between those of the two different species. Knapic et al. studied about variation in wood stiffness of eucalyptus and concluded that the variation was explained by microfibril angle (MFA) and wood density variations [11]. The innerwood veneer contained juvenile wood which differed from mature wood in MFA and density. Ishidoh et al. found a negative correlation MFA and Young's modulus or specific Young's modulus for sugi wood [12]. Specific Young's modulus showed stronger coefficient correlation ($r = -0.889$) than Young's modulus ($r = -0.747$). They concluded the Young's modulus can be evaluated using MFA value at an early stage of growth. The specific Young's modulus results obtained from dividing the MOE by the density is shown in Fig. 8. The difference in the modulus between Pi-LVL and Po-LVL was not statistically significant. In case of poplar veneer, a difference between the innerwood and outerwood densities was observed, while a relatively small difference was observed in the physical properties in cell wall between Pi-LVL and Po-LVL. It implies the MFA of cell wall was similar between innerwood and outerwood. In the eucalyptus veneer, the specific Young's modulus of Ei-LVL was significantly smaller than that of Eo-LVL ($p<0.05$). In the eucalyptus veneer, the innerwood and outerwood differed in terms of density as well as in terms of MFA of the cell wall, which caused a significant difference, in terms of physical properties, between Ei-LVL and Eo-LVL. Mixed LVL (PiEo and PoEi) had intermediate values. The specific Young's modulus of the mixed-species LVL and the average of the specific Young's modulus of the two types of mono-species LVL are shown in Fig. 9. PiEo-LVL was smaller than the average values of Pi-LVL and Eo-LVL; however, PoEi-LVL was much greater than the average values of Po-LVL and Ei-LVL, whereas it was equal to the average values of Po-LVL and Eo-LVL. The cell wall of the Ei veneer that PoEi-LVL comprised was similar to that of the outerwood veneer, whereas its density was smaller than that of outerwood veneer because the Ei veneer sheets were selected at some distance from the pith, not from near the pith, to equalize their density with that of the Po veneer sheet.

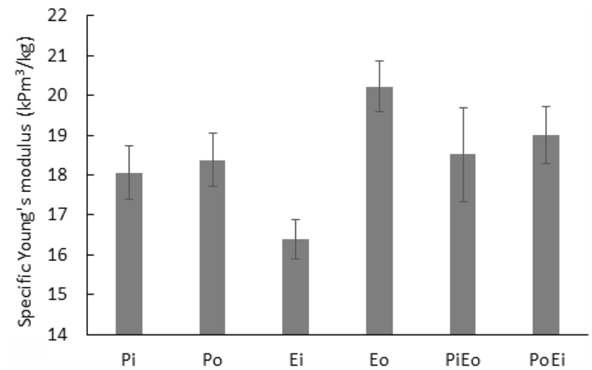

Fig. 8 Specific Young's modulus of the manufactured LVL for the bending test

Table 3 Properties of the manufactured LVL for the bending test

Species	Poplar		Eucalyptus		Mixed	
Veneer type	Pi	Po	Ei	Eo	PiEo	PoEi
Num	10	10	10	10	10	10
Density (kg/m^3)						
AVG	547	618	581	701	586	587
STD	10	11	12	8	11	12
MOE (GPa)						
AVG	9.9	11.4	9.5	14.2	10.8	11.3
STD	0.4	0.4	0.3	0.5	0.7	0.4
M.C (%)						
AVG	9.3	8.7	9.2	9.6	9.7	9.7
STD	0.6	0.2	0.3	0.6	0.7	0.2

MOE modulus of elasticity, *AVG* average value, *STD* standard diviation

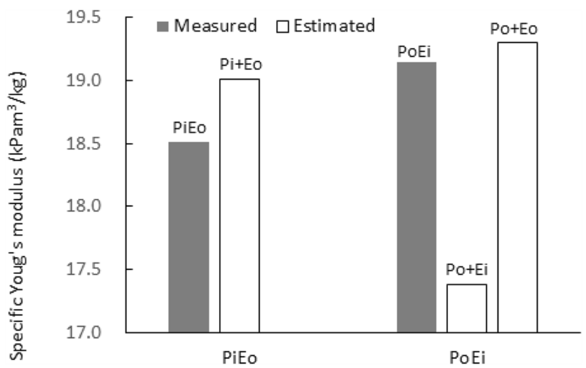

Fig. 9 Comparison between the mixed-species LVL and the average of two types of mono-species LVL in specific Young's modulus

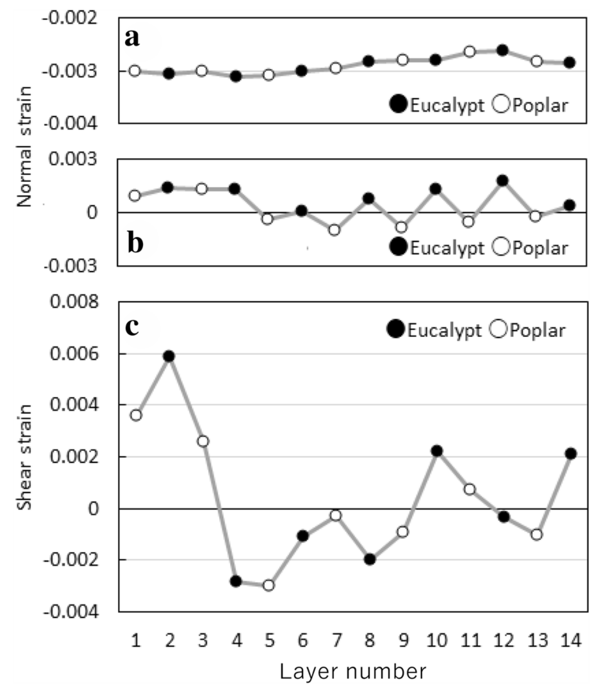

Fig. 10 Strain distribution of the mixed-species 17-ply LVL (PE-LVL) along the laminated direction; horizontal axis: layer number; **a** normal strain in the loading direction, **b** normal strain in the laminating direction, **c** shear strain

Strain distribution from the compression test

When a beam is loaded downward in the bend test, tensile deformation occurs on the bottom surface and compression deformation occurs on the upper surface in the fiber direction. We measured the strain distributions by using the compression test to understand the results of the bending test. Images were captured just after the load deviated by 1% or more from the approximate straight line in the elastic region of the load-deformation curve to analyze the elastic region. Examples of the strain distribution obtained from the DIC analysis are shown in Figs. 10 and 11. The strain distribution of the mixed-species 17-ply LVL (PE-LVL) that was parallel to the laminating direction is shown in Fig. 10b. In the fiber direction compression test, we expected that the same amount of compression strain would appear in the loading direction of both poplar and eucalyptus layers, while tensile strain would appear normal to the direction based on its Poisson's ratio. However, a larger tensile strain occurred in the eucalyptus layers with high density and a smaller tensile strain was found in the poplar layers with low density in the laminating direction. In some of the poplar layers vertical strains (parallel to the laminated direction), as high as in the eucalyptus layers, were observed, whereas large shear strain was observed in the eucalyptus layers. A similar tendency was seen among other mixed LVL. Normal strain distributions of P-LVL, E-LVL, and PE-LVL are shown in Fig. 11. Mono-species LVL (P-LVL and E-LVL) did not change in a way similar to that of the mixed LVL but were relatively uniform. The strain distribution seen in Fig. 10 was unique to the mixed LVL.

Effect of alternating lamination by using different density veneers

A previous study reported the warpage mitigation mechanism of LVL by alternating lamination of rubberwood and falcata veneer [13] and explained that the falcata layers mitigated large deformation behavior of rubberwood layers induced by moisture content change. The present study observed the strain in the fiber direction from the compressive test. In LVL that is composed of alternating layers of high-density sheets and low-density sheets, an applied load is distributed depending on the density of each sheet when both layers are of the same thickness. The MOE of the high-density layer affects the entire specimen more than that of the low-density layer. In the mixed LVL, which consisted of poplar and eucalyptus veneers, the high density of the eucalyptus veneers made a significant contribution to the overall rigidity. Considering these strain distributions, eucalyptus veneer layers behaved as thin plates (Fig. 12b). Thin plates are deformable in-plane in the plane-stress state or out-of-plane owing to buckling under in-plane compression (Fig. 12c). The small normal strain in the poplar layer (Fig. 10b) and shear strain in the eucalyptus layer (Fig. 10c) implied thin-plate behavior. However, each layer in the mono-species LVL did not show deformation similar to that of the thin plates but rather was deformed in a plane-strain state and the strain distribution was uniform. The difference between the measured (PoEi) and predicted (Po + Ei) bending rigidity was attributed to the tendency

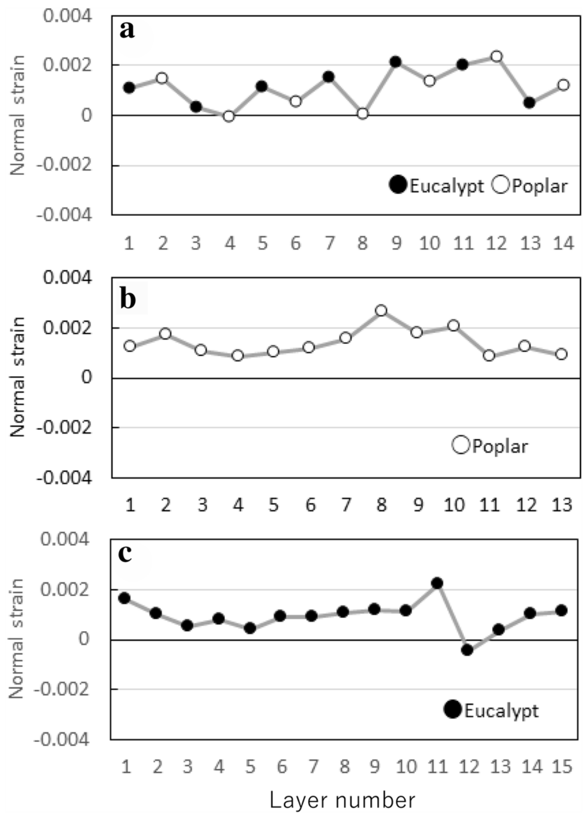

Fig. 11 Normal strain distribution in the laminating direction: horizontal axis: layer number, **a** PE-LVL, **b** P-LVL, **c** E-LVL. Figure **a** is a different specimen from Fig. 10

of the eucalyptus layer to deform as thin plates, that is, the deformation of the soft layers absorbed that of the hard layers in the mixed LVL.

The Chinese eucalyptus used in the present study is a sustainable resource that is produced in plantation forests, and thus, its effective utilization leads to natural forest protection. However, eucalyptus properties have large variations, such as in terms of physical properties between the innerwood and outerwood. To increase yield and reduce costs, the entire material should be used; however, the variation in material is disadvantageous for its industrial use. In mixed LVL that contains alternating laminated hard eucalyptus and soft poplar veneers, the material quality of fast-growing wood was improved by the mitigation of eucalyptus deformation by the poplar layer.

Conclusion

The present study explained the effect of alternating lamination of eucalyptus and poplar veneer sheets on the mechanical properties of LVL for the use of Chinese eucalyptus as a material for interior building purposes. We investigated the wood resources in China and the physical properties of LVL. The following results were found:

1. Eucalyptus accounts for 24 million cubic meters of the wood production produced in 2018 in Guangxi province, China. Eucalyptus is a sustainable hardwood resource because fast forestry by eucalyptus has a rotation cycle of less than 10 years which enables efficient timber production.
2. The eucalyptus and poplar veneers were obtained by serially slicing logs with a rotary lathe and were evaluated. It was found that the innerwood sheets had low density and were juvenile for both poplar and eucalyptus. The eucalyptus innerwood LVL demon-

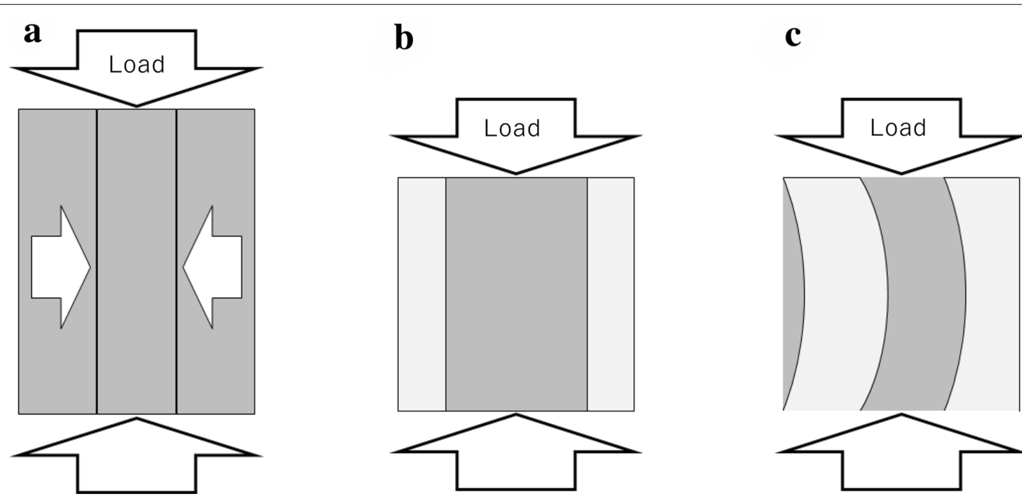

Fig. 12 Deformation models of the hard species veneer of LVL in the compression tests; **a** plane-strain model in the mono-species LVL, **b** plane-stress model in the mixed-species LVL, **c** buckling model in the mixed-species LVL

strated small specific Young's modulus. Thus, the cell wall of the eucalyptus innerwood veneer may have different composition from its outerwood.

3. The measured MOE of the mixed LVL (PiEo-LVL), consisting of alternating layers of low-density innerwood poplar veneer and high-density outerwood eucalyptus veneer, was smaller than the predicted quantity from the mono-specific LVL. Therefore, the alternating lamination had some effect on mitigating dispersion in MOE.
4. We found characteristic normal and shear strains in the soft poplar layers. As a result, high-density eucalyptus layers behaved similar to thin sheets and low-density poplar layers absorbed the deformation of the eucalyptus layers.

Although the quality of the eucalyptus veneer sheets was not stable, alternating lamination with poplar sheets makes it possible for the quality variations of eucalyptus to be absorbed by that of the poplar and improve the variation in the MOE. Eucalyptus is a sustainable wood resource and wood material quality stabilization technology is effective for natural forest conservation.

Abbreviations

LVL: Laminiated veneer lumber; Pi: Poplar, innerwood; Po: Poplar, outerwood; Ei: Eucalyptus, innerwood; Eo: Eucalyptus, outerwood; PiEo: Poplar, innerwood, and eucalyptus, outerwood; PoEi: Poplar, outerwood, and eucalyptus, innerwood; MOE: Modulus of elasticity; DIC: Digital image correlation; MFA: Microfibril angle; P-LVL: Poplar laminated veneer lumber; E-LVL: Eucalyptus laminated veneer lumber; PE-LVL: Poplar and ecalyptus laminated veneer lumber.

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Authors' contributions

KM, MN and KM carried out all the experiments, analysis and manuscript writting. NY and YY gave information and supported to prepare specimen. KY, MN and KU gave the suggestion to the interpretation of the data. All authors read and approved the final manuscript.

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Availability of data and materials

The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Competing interests

The authors declare that they have no competing interests.

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