J Wood Sci (2001) 47:115–123

ORIGINAL ARTICLE

Toshihiro Hata · Kenji Umemura · Hidefumi Yamauchi
Akihiro Nakayama · Shuichi Kawai · Hikaru Sasaki

Design and pilot production of a "spiral-winder" for the manufacture of cylindrical laminated veneer lumber

Received: November 16, 1999 / Accepted: May 12, 2000

Abstract A new spiral-winder was developed for continuous manufacturing of cylindrical laminated veneer lumber (LVL), and a suitable resin adhesive for this cylindrical LVL manufacturing system was investigated. This phase was followed by trial manufacturing and evaluation of cylindrical LVL with the optimum resin adhesive identified. The results are summarized as follows. (1) The shortest gelation time was recorded with a mixture of two commercial resorcinol based resins (DF-1000 and D-33) at a weight ratio of 25:75. (2) Bath temperature had a remarkable effect on the gelation time of the adhesive mix. (3) High bonding strength was recorded by 25:75 DF-1000/D-33 adhesive mix at a high press temperature despite a short pressing duration. Based on the results of items (1) to (3), 25:75 DF-1000/D-33 is recommended for use in the new spiral-winder. (4) The mechanical properties of cylindrical LVL could be improved by using 25:75 DF-1000/D-33 with wider veneer width and longer pressing time. (5) The mechanical properties, especially the modulus of rupture, of the cylindrical LVL manufactured require further improvement for practical structural application.

Key words Cylindrical LVL · Spiral-winder · Belt-pressing · Resin formulation · Mechanical properties

T. Hata (✉) · K. Umemura · S. Kawai
Wood Research Institute, Kyoto University, Gokasho, Uji, Kyoto 611-0011, Japan
Tel. +81-774-38-3677; Fax +81-774-38-3678
e-mail: hatatoshihiro@hotmail.com

H. Yamauchi · H. Sasaki
Institute of Wood Technology, Akita Prefectural University, Noshiro 016-0876, Japan

A. Nakayama
Showa Marutsutsu Co., 8-1 Sakura-Cho, Higashi-Osaka, Osaka 579-8047, Japan

Introduction

An increase in the demand for environmentally friendly materials has resulted in laminated veneer lumber (LVL) to gain importance, as it can be manufactured from sustainable wood resources. Because of its low energy requirement and high production yield, LVL has become popular, especially as a highly reliable engineered wood product.

Among the many distinctive features of wood as a structural material is its low density with high specific strength, mainly due to its special cellular structure.[1,2] Consequently, many materials used for structural applications in airplanes and spacecrafts (e.g., fiber-reinforced plastics, or FRPs), are designed based on the structure of the wood cell wall.[3,4] The design of cylindrical LVL originates from the same principle.

In a preliminary study, we investigated the possibility of continuous manufacturing of cylindrical LVL using the conventional equipment used for rolled-paper production. The results obtained gave a positive indication of manufacturing cylindrical LVL by applying the above technology based on the spiral-winding method. Different from rolled-paper production, however, it is necessary to apply thermosetting adhesive during the manufacture of structural cylindrical LVL.

This study aims to develop a new spiral-winder equipped with a special heating device for the continuous manufacturing of cylindrical LVL. Different from conventional hot-platen pressing, belt-pressing is used for this manufacturing technology. Because belt-pressing allows only a short press duration, an appropriate resin adhesive that can cure rapidly under high temperature is needed.

Our previous study showed that it was possible to achieve a short gelation time (78 s) at ambient temperature (20°C) by mixing a rapid curing resin and a conventional resorcinol resin in a 1:2 ratio (w/w). At 20°C, however, this adhesive mix required a press time of more than 3 min to produce a tensile shear (bonding) strength of 3.8 MPa.[5]

Subsequent efforts were made to determine the optimum mixing ratio of the above resins for rapid curing under

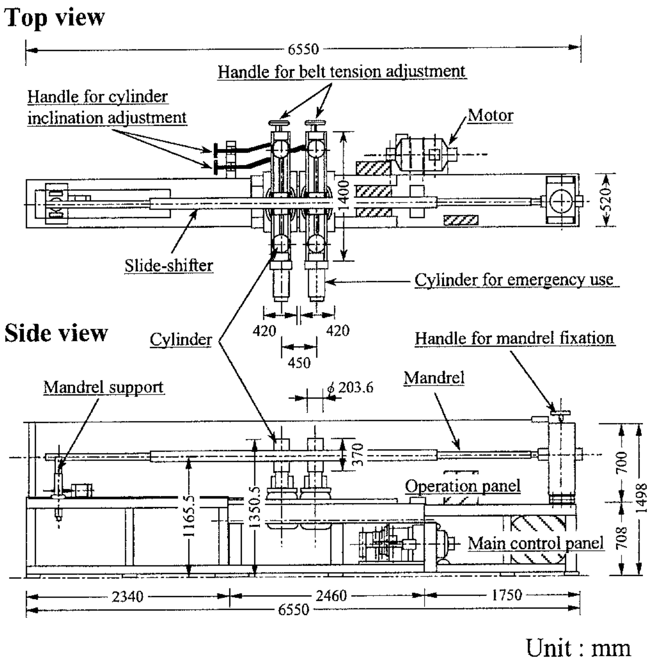

Fig. 1. Parts of the spiral-winder

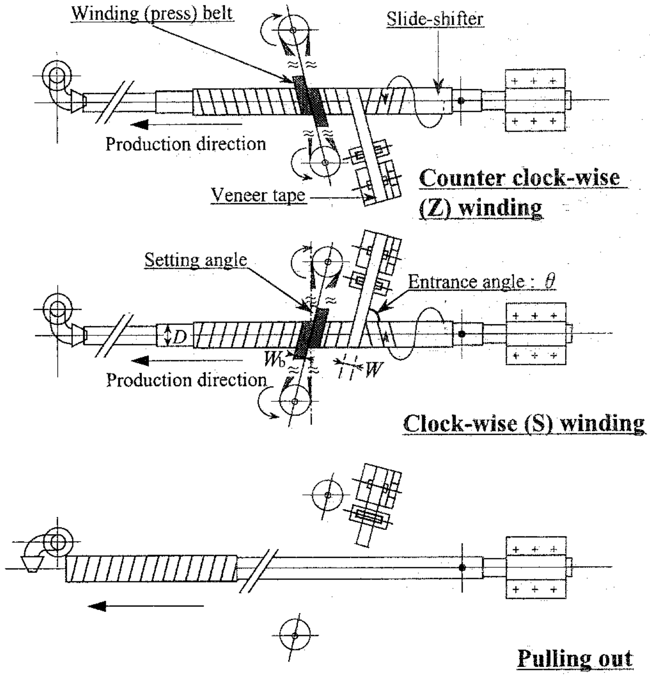

Fig. 2. Relations among production direction, the entrance direction of the veneer tape, and the setting angle of the cylinder

high temperature. This phase was followed by fabrication of cylindrical LVL using the spiral-winder and evaluation of its mechanical properties.

Experiments

Design and production of a spiral-winder equipped with a slide-shifter

To begin with, the effects of various fundamental parameters underlying this new technology of continuous manufacturing of cylindrical LVL were investigated to determine the optimum combination of manufacturing conditions. In this study, a new spiral-winder equipped with a mobile slide-shifter on a mandrel with uniform diameter was designed and manufactured. The main factors being taken into consideration for the design of this spiral-winder included (1) the inner and outer diameters and length of the product, and (2) the winding pattern.

Figure 1 illustrates the design of the newly developed spiral-winder, and Fig. 2 represents the relations among the clockwise/counterclockwise winding directions, the entrance angle of the veneer tape, and the setting angle of the cylinder on the spiral-winder. The systems on this spiral-winder are (1) an inner diameter of cylindrical LVL ranging from 30 to 125 mm by altering the size of the slide-shifter on the mandrel, and (2) an outer diameter of 40–150 mm. In this study, the diameter of the slide-shifter used was 80 mm. The maximum length of the cylindrical LVL, which is dependent on the length of slide-shifter, is 3200 mm.

Because flat LVL with interlocked structure was reported to have a greater tensile Young's modulus than noninterlocked LVL,[6] the new spiral-winder was designed to wind veneer tapes in both the clockwise and counterclockwise directions to produce an interlocked winding pattern.

The pressure (p) exerted on the cylindrical LVL by the rubber belt during winding is calculated as:

$$p = \frac{2T\sin^2\theta}{\left[D + 2nt(1 - \varepsilon)\right]W_b} \tag{1}$$

where T is the tensile force of the rubber belt; θ is the entrance angle of the rubber belt and the veneer tape; D is the diameter of the slide-shifter; n is the ply number; t is the thickness of the veneer tape; ε is the transverse compressive strain of the veneer tape; and W_b is the width of the rubber belt.

In this study, the transverse compressive strain of the veneer tape was ignored because of its negligible magnitude. The tensile force (T) of the rubber belt was calculated based on the relation between the tensile Young's modulus and the strain of the belt. The strain of the rubber belt was measured when tensile force was applied to the cylindrical LVL at the 4th, 8th, and 12th layers, respectively. The pressure calculated was 0.80–0.85 MPa under D of 80 mm, t of 1 mm, θ of 80°, and W_b of 50 mm.

In this continuous manufacturing process, the winding speed (angler velocity) can be set at 2.3–23.8 rad/min (conventional) or 7.5–75.0 rad/min by changing the sprockets. A cylindrical heater is attached to the spiral winder (Fig. 3A) to attain a sufficiently high glue-line temperature within the short pressing duration. This 800-W powered heater has an inner diameter of 120 mm and length of 600 mm. Figure 4 shows the relation between the time and surface tempera-

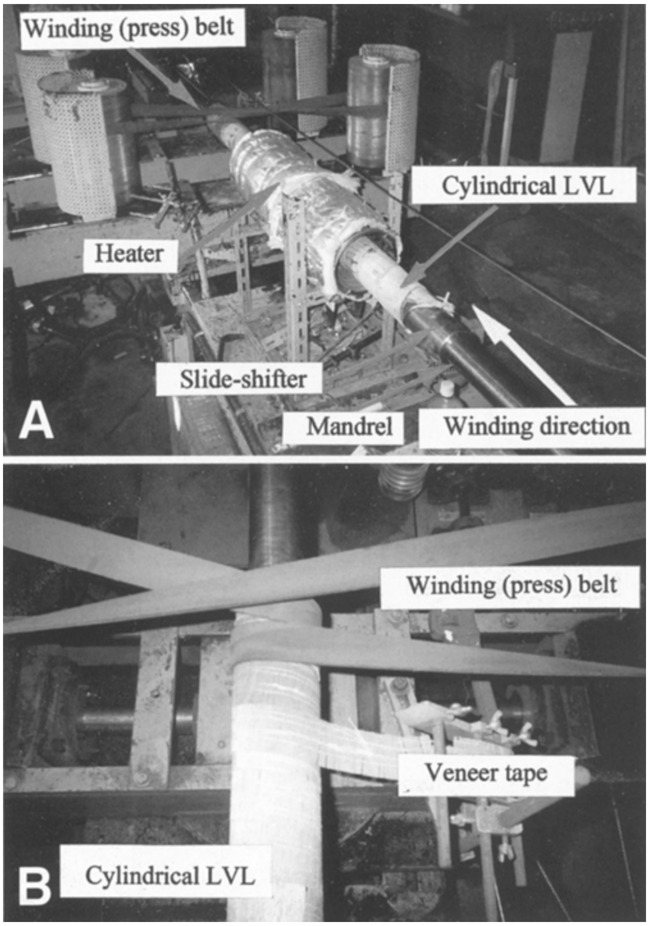

Fig. 3. Manufacturing process of cylindrical laminated veneer lumber (LVL). **A** Appearance of spiral-winder and pilot installed cylindrical heater. **B** Close-up view

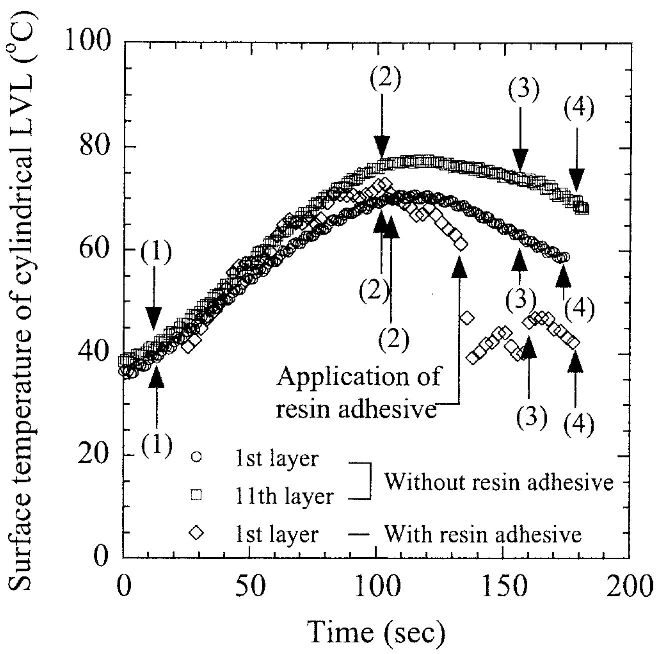

Fig. 4. Relations between time and surface temperature of cylindrical LVL. (*1*), (*2*), (*3*), (*4*) represent the initiation of heating, end of heating, initiation of pressing, and end of pressing, respectively, at a winding speed of 18.8 rad/min

ture of cylindrical LVL passing through the heating device on the spiral-winder in the absence and presence of resin adhesive. For the surface temperature without resin adhesive, the temperatures of the 1st layer (farthest from the heat source) and 11th layer (closest to the heat source) remained constant at about 60°C and 70°C, respectively, during belt-pressing at a winding speed of 18.8 rad/min. With resin adhesive, the first layer recorded a temperature of 45°–50°C during pressing at the same winding speed.

Selection of resin adhesives and manufacture of cylindrical LVL

Measurement of gelation time

Based on the previous report,[5] two resorcinol-based resin adhesives – a rapid-curing resorcinol-based resin adhesive for wood finger jointing (DF-1000) and a resorcinol resin for structural use (D-33) – were used. Both of these resins were formulated by Oshika-Sinko Company. For DF-1000 the resin and resin hardener were liquids, and the mixing ratio was 1:1 (w/w). On the other hand, the resin and resin hardener of D-33 were liquid and powder (paraformaldehyde/coconut shell powder, 1:1), respectively, and the mixing ratio was 1.0:0.2 (w/w). Therefore, the DF-1000 and D-33 resins were first mixed together, and the mixture of their hardeners were then added to the resin mix. In addition to the hardeners, 10% of filler (coconut shell powder) was added to the resin mix based on the total weight of the resin mix. The gelation time for the adhesive mix ratios of DF-1000/D-33 of 100:0, 75:25, 50:50, 25:75, and 0:100 (weight basis) at 25°, 50°, 80°, 100°, 130°, 150°, and 180°C were determined in accordance with the Japanese Industrial Standard for Phenolic Resin Adhesives for Wood (JIS K6802 1995).[7] A waterbath was used for temperatures below 100°C, whereas an oil bath was used for 100°C and above.

Measurement of tensile shear strength

To determine the optimum combination of hot-pressing temperature and the mixing ratio of DF-1000 and D-33, samples of three-ply plywood (200 × 200 mm) were manufactured using various conditions. Rotary peeled 1.0–1.5 mm thick lauan (*Shorea* spp.) veneers were used. Table 1 summarizes the manufacturing conditions of the three-ply plywood. A thermocouple was inserted between the top and core veneers to measure the variation in temperature at the glue-line during hot-pressing at 50°, 80°, and 100°C. The plywood manufactured was conditioned for about 2 weeks prior to evaluation of dry and wet tensile shear strengths based on Japanese Industrial Standard for Testing Method for Tensile Shear Strength of Wood-to-wood Adhesive Bonds (JIS K6851 1994).[8] For the wet tensile shear test the

Table 1. Manufacturing conditions of three-ply plywood

Resin mix ratio of DF-1000/D-33 (weight basis)	100:0, 25:75, 0:100
Press pressure (MPa)	1.0
Press temperature (°C)	25, 50, 80, 100
Press time (s)	5, 15, 30, 60
Resin spread (g/m^2)	200
Filler (% based on resin weight)	10

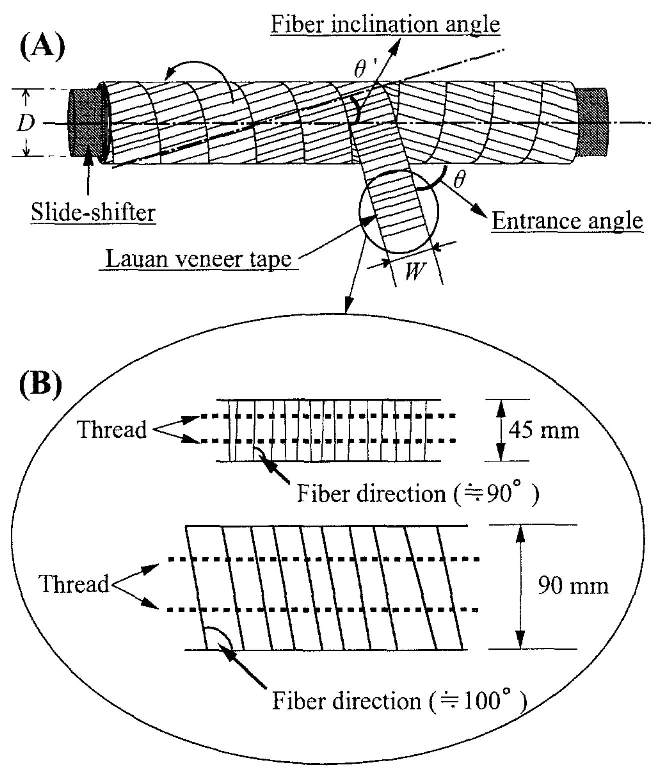

Fig. 5. Cylindrical LVL manufacturing process (**A**) and an enlargement of the sewn lauan veneer tape (**B**)

samples were boiled for 4 h, dried at 60°C for 24 h, boiled for another 4 h, cooled, and tested when the samples were still wet.

Manufacture of cylindrical LVL

When the fiber direction of the veneer tape was perpendicular to the longitudinal direction of the tape, as shown in Fig. 5, the width of the tape (W) was determined using the following equation:

$$
\begin{aligned}
W &= \left[D + 2(n-1)t(1-\varepsilon)\right]\pi \cos\theta \\
&= \left[D + 2(n-1)t(1-\varepsilon)\right]\pi \cos\left(\frac{\pi}{2} - \theta'\right) \qquad (2) \\
&= \left[D + 2(n-1)t(1-\varepsilon)\right]\pi \sin\theta'
\end{aligned}
$$

where D is the diameter of the slide-shifter; n is the ply-number; t is the thickness of the veneer tape; ε is the transverse compressive strain of the veneer tape; θ is the entrance angle of the veneer tape; and θ' is the inclination angle of the fiber to the longitudinal direction of the slide-shifter.

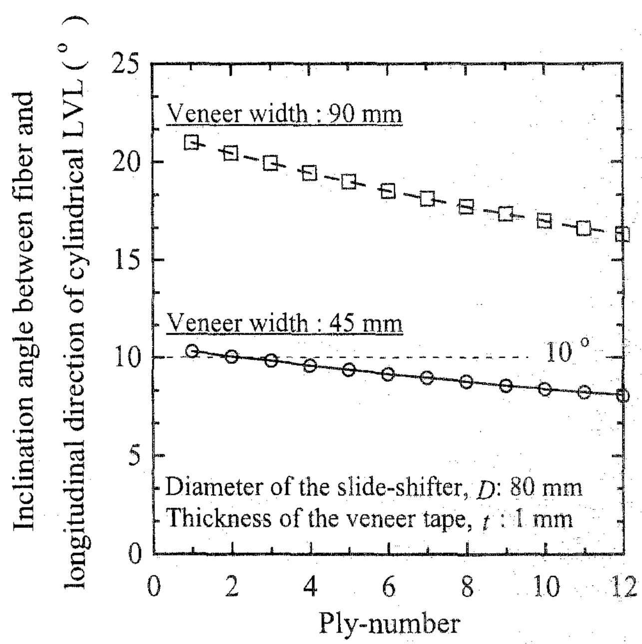

Fig. 6. Relations between ply number and calculated fiber inclination angle to the longitudinal direction of cylindrical LVL

Figure 6 shows the relation between ply number and calculated fiber inclination angle to the longitudinal direction of cylindrical LVL. For cylindrical LVL with an interlocked structure, the inclination between the fiber and longitudinal direction of cylindrical LVL must be set within 10° to achieve a maximum strength of the product.[6,9] When 1 mm thick veneer tape was wound on a slide-shifter of 80 mm diameter, the optimum width of the tape was calculated to be 43.6 mm. If a 45 mm wide veneer tape were used, however, the fiber inclination angle would be within 10° in the second and succeeding layers. Consequently, rotary peeled 1 mm thick/45 mm wide lauan (*Shorea* spp.) veneers were prepared. When short pieces of 1 mm thick/45 mm wide veneers were sewn to produce a long veneer tape, a polyester thread was used to ensure the endurance of this veneer tape against the tensile force exerted on it during the spiral winding process.

At an equal winding speed, the productivity of cylindrical LVL is doubled when 90 mm wide veneer tape is used instead of 45 mm tape. Furthermore, the number of butt joints, which contribute to the structural defects in the product, is also reduced. Therefore, we attempted to manufacture cylindrical LVL from 90 mm wide veneer tape. However, when a 90 mm wide veneer tape is used in the same way as 45 mm wide veneer tape, the fiber inclination angle would exceed 10° (Fig. 6). Consequently, short pieces of rotary peeled 1 mm thick/90 mm wide veneers were prepared and sewn with the veneer fiber direction running 100° to the length of the veneer tape, as illustrated in Fig. 5B.

During the continuous manufacturing of cylindrical LVL the resin was brushed onto the preheated surface of the veneer tape, and the hardener was applied to the complementary surface of the following layer using a hand roller. The resin spread ratio was about 180 g/m^2 based on the solid content.

A total of six cylindrical LVLs were trial-manufactured using the optimum combination determined in the earlier sections (i.e., minimum belt-pressing temperature 45°–50°C at 0.80–0.85 MPa for 21 s using a resin mix of 25:75 DF-1000/D-33. For easy workability, the veneer tape was interlocked at every two-layer interval, and the total ply numbers of the cylindrical LVL produced were 4, 8, and 12. One sample was manufactured for each combination of the production conditions. With this trial manufacturing, a positive result concerning the possibility of continuous manufacturing of cylindrical LVL was obtained. However, some delaminations between veneers were observed partially at 8- or 12-ply numbers, which could have been caused by insufficient production accuracy. Therefore, following the bending test, three four-ply cylindrical LVLs were manufactured by various combinations of veneer width and press time (i.e., 45 mm/21 s, 45 mm/42 s, and 90 mm/42 s), under the same manufacturing conditions noted above. The diameter of the slide-shifter used was 80 mm. When the 45 and 90 mm wide veneer tapes were used, the widths of the winding belts used were 50 and 100 mm, respectively. Figure 3B shows the manufacturing process for cylindrical LVL.

Bending test of cylindrical LVL

The three-point static bending test was conducted at a cross-head speed of 5 mm/min. To prevent lateral deformation of the cylindrical LVL, three special metal holders were installed at the loading and supporting points.[10] Curved metal plates were inserted between the cylindrical LVL and the holders at the supporting points to prevent the cylindrical LVL from sinking into the holders, as illustrated in Fig. 7. The displacement was measured using a displacement transducer set under the cylindrical LVL at the center of the span. The experimental Young's modulus (MOE) of the

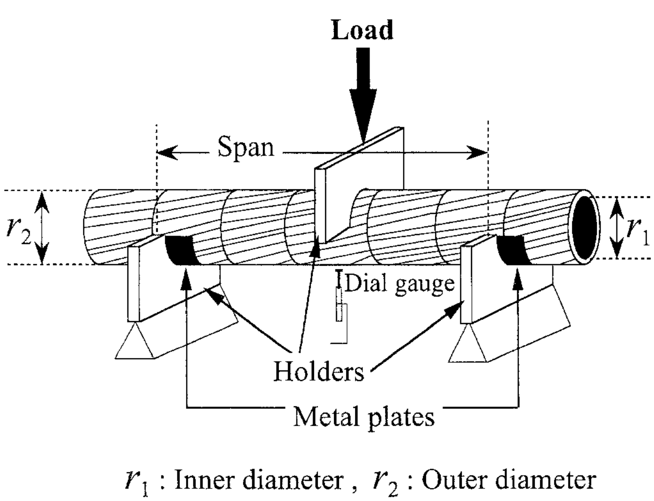

Fig. 7. Setup for the static bending test of cylindrical LVL

cylindrical LVL was measured at span (L) to outer diameter (r_2 88 mm) ratios (L/r_2) of 5, 7, 9, and 11. The modulus of rupture (MOR) was measured at an L/r_2 of 11. MOE (E) and MOR (σ) were calculated using the following equations.

$$\mathrm{MOE}\ (E) = \frac{(dP/d\delta)L^3}{48I} = \frac{4(dP/d\delta)L^3}{3\pi\left(r_2^4 - r_1^4\right)} \tag{3}$$

$$\mathrm{MOR}\ (\sigma) = \frac{M}{Z} = \frac{8P_{\max}Lr_2}{\pi\left(r_2^4 - r_1^4\right)} \tag{4}$$

where ($dP/d\delta$) is the gradient of the load-deflection line within elastic deformation; L is the span; I is the moment of inertia of the area; r_1 and r_2 are the inner and outer diameters of cylindrical LVL; M is the moment; Z is the section modulus; and $P_{\max}$ is the maximum load. The cylindrical LVL was set to locate the butt joint at the tensile side under the loading point.

Results and discussion

Gelation time

Figure 8A shows the effects of the resin mix ratio of DF-1000 and D-33 on the gelation time. As the proportion of D-33 increased, the gelation time had a tendency to decrease gradually; the shortest gelation time was recorded at 25:75 DF-1000/D-33. This could be attributed to a reduction in the amount of solvent in the adhesive mix to be vaporized, as the content of D-33, whose hardener is powder, increases. Generally, adhesives with higher solid content cure faster.[11] For neat D-33 (i.e., at 0:100 DF-1000/D-33), however, a long gelation time was recorded. This could be due to the absence of meta-aminophenol in DF-1000, which is responsible for accelerated co-polycondensation of resorcinol.[5]

Subiyanto et al.[12] reported the gelation time of adhesive to be dependent on the adhesive type and heat energy obtained from the waterbath. In this study the temperature of the adhesive mix was not measured directly; but the waterbath or oil bath temperature had a marked effect, as the gelation time was found to decrease with increasing temperature (Fig. 8B). For example, when the bath temperature was higher than 80°C, the gelation time of the resin mix at 25:75 DF-1000/D-33 was reduced to below 30 s.

Bonding strength of three-ply plywood

Figure 9 shows the relations between press time and dry bonding strength of three-ply plywood bonded with different resin mixes and cured at various temperatures. Press time was found to have a significant effect on the dry bonding strength at all resin mix ratios. In the case of 100:0 DF-1000/D-33, plywood could be produced under an extended press time of 15 s at a press temperature of 80°–100°C.

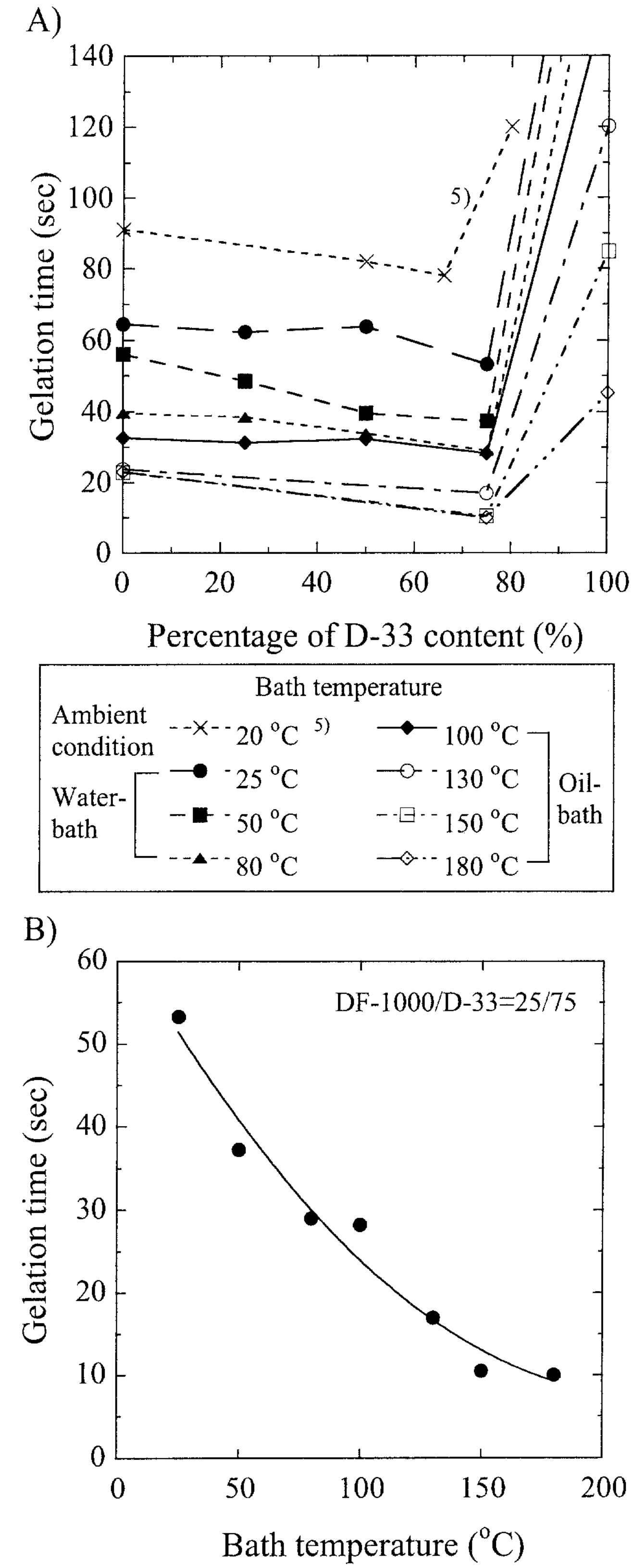

Fig. 8. **A** Effects of resin mix ratio and bath temperature on gelation time. The number "5" is a reference number. **B** Relations between gelation time and bath temperature at DF-1000/D-33 25:75

Although the bonding strength of various resin mixes can be improved by extending the press time, plywood manufactured with 25:75 DF-1000/D-33 recorded the highest dry bonding strength, irrespective of the press temperature or press time. In the case of 0:100 DF-1000/D-33, plywood could not be produced at a press temperature of 100°C, even when the press time was extended to 60s. Judging from the results of the gelation time in the earlier section, the press time may have to be extended. Different from when the respective neat resins (i.e., 100:0 or 0:100 DF-1000/D-33) were used, the bonding strength of plywood samples manufactured using 25:75 DF-1000/D-33 was markedly improved, with a short pressing time of 5–15s. Despite using a press time as short as 5s, bonding strengths of 1.1 and 1.3MPa were recorded at press temperatures of 80° and 100°C, respectively. Although no specific correlation was observed among the percentages of wood failure, press time, and press temperature, plywood samples manufactured using 25:75 DF-1000/D-33 registered substantially higher values than the neat resins.

Figure 10 shows the relations between press time and wet bonding strength of the plywood samples produced under different press temperatures. The wet bonding strength recorded was slightly lower than the dry bonding strength. Similar to the dry condition, the wet wood failure showed no specific correlation with pressing temperature or duration. Despite being expensive because of its fast curing nature, DF-1000 has low water-repellent ability. By utilizing a resin mix of 25:75 DF-1000/D-33, it is possible to improve not only the cost efficiency but also the water repellence of this resin.

Glue-line temperature of three-ply plywood

Figure 11 shows the changes in glue-line temperature in three-ply plywood bonded with 25:75 DF-1000/D-33 during hot-pressing at 50°, 80°, and 100°C. The increase of the glue-line temperature was, in general, considered to be rather slow owing to the high heat capacity of wood. In this experiment, however, the rate of increase in the glue-line temperature was remarkably rapid, reaching the hot press platen temperature almost immediately, as the veneers used were thin. Moreover, the rate of temperature increase was faster at higher hot platen temperatures. For example, at a hot platen temperature of 100°C, the glue-line temperature rose rapidly to 40°–50°C after hot-pressing for 5–15s. This indicates the possibility of applying 25:75 DF-1000/D-33 for continuous manufacture of cylindrical LVL using a minimum curing temperature of 40°–50°C.

The surface temperature of the first layer of cylindrical LVL spread with resin was lower than that without resin, as shown in Fig. 4. However, the temperature and thermal capacity of the cylindrical LVL could be increased by increasing the ply number. Therefore, a glue-line temperature of 40°C or higher is expected to be maintained during the belt-pressing of cylindrical LVL manufacturing under a similar winding speed of 18.8 rad/min and veneer thickness of 1mm.

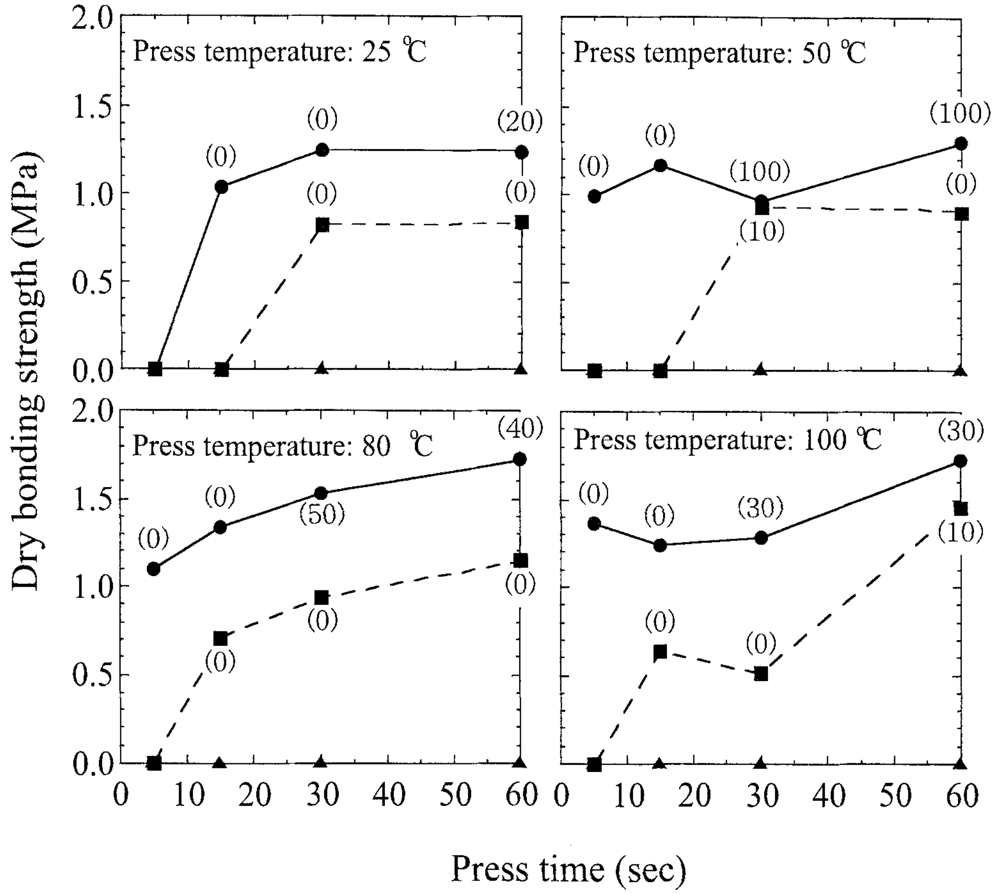

Fig. 9. Relations between press time and dry bonding strength. DF-1000/D-33 ratios: 100:0 (*squares*), 25:75 (*circles*), and 0:100 (*triangles*). Each plot is the mean value for six specimens. Figures in parentheses are the average values of the percent of wood failure

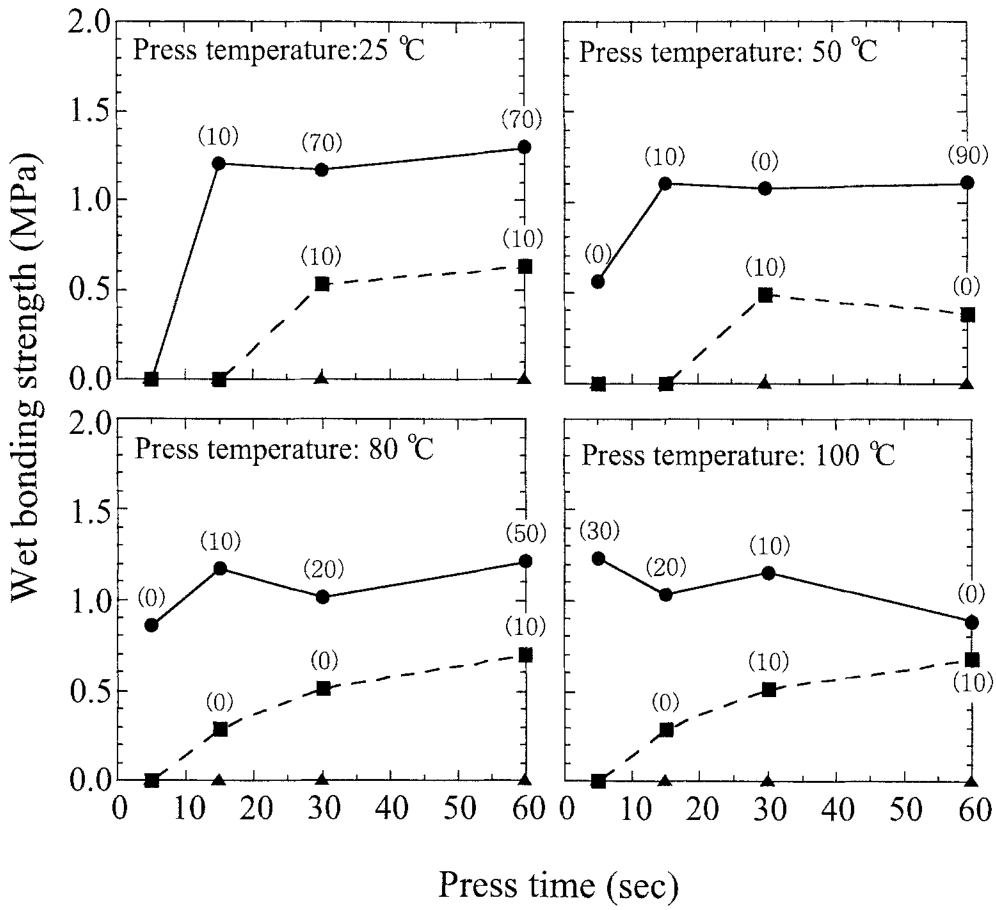

Fig. 10. Relations between press time and wet bonding strength. See Fig. 9 for an explanation of the symbols

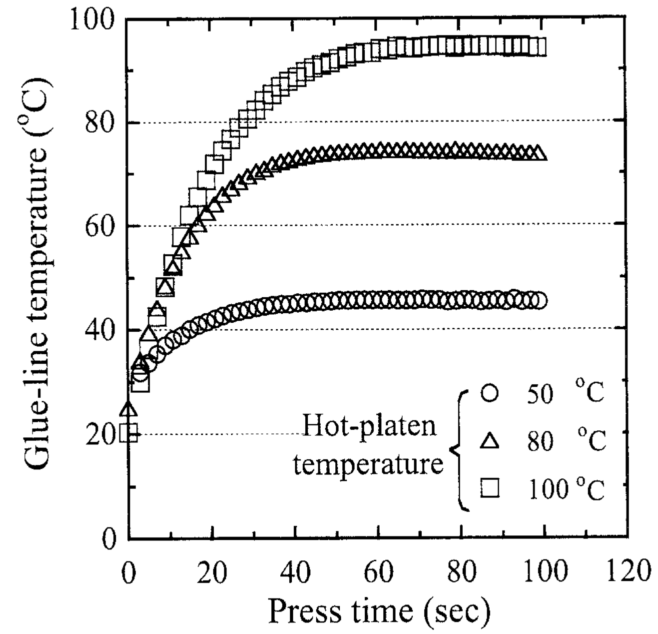

Fig. 11. Variation of glue-line temperature in three-ply plywood during hot-platen pressing. DF-1000/D-33 ratio is 25:75

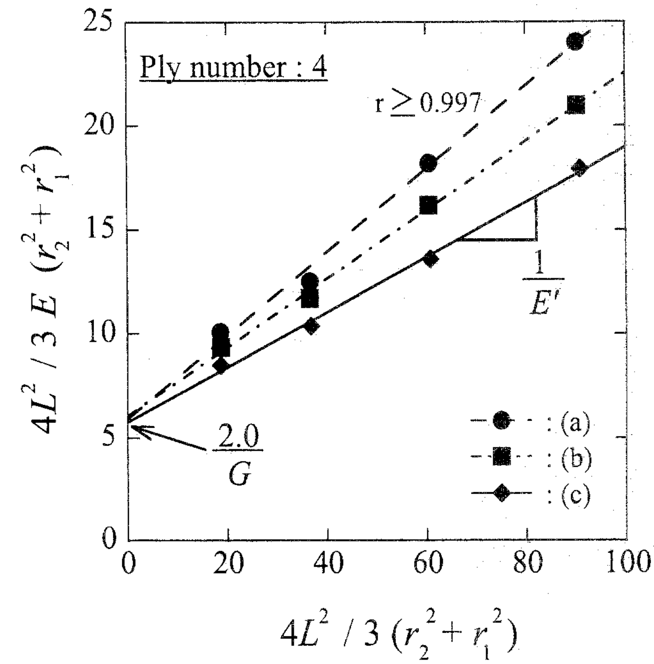

Fig. 12. Estimation of Young's modulus (E') and modulus of rigidity (G). (*a*) Veneer width 45 mm, press time 21 s. (*b*) Veneer width 45 mm, press time 42 s. (*c*) Veneer width 90 mm, press time 42 s. Productivity in (*a*) and (*c*) are equal, but in (*b*) it is half

Mechanical properties of cylindrical LVL

In this study the span/outer diameter ratio was 11:1. According to the JIS, the span/thickness ratio in the bending test should be more than 14:1. Therefore, the effect of shear was assumed to be more than expected to obtain real bending properties. To eliminate the marked effect of shear, the value of real Young's modulus (E') was estimated using the following equation.[13–16]

$$\delta_{\mathrm{total}} = \delta_{\mathrm{bend}} + \delta_{\mathrm{shear}}$$

$$\frac{PL^3}{48EI} = \frac{PL^3}{48E'I} + \frac{\kappa PL}{4GA} \tag{5}$$

where δ is the deflection; P is the load; L is the span; E is the experimental Young's modulus; G is the modulus of rigidity; I is the moment of inertia of the area; A is the cross-sectional area of cylindrical LVL; and κ is the modulus of shear deformation (2.0).[17]

When I and A in Eq. (5) are substituted with the actual measurements of the cylindrical LVL, we have

$$\frac{4L^2}{3E\left(r_2^2 + r_1^2\right)} = \frac{4L^2}{3\left(r_2^2 + r_1^2\right)} \cdot \frac{1}{E'} + \frac{\kappa}{G} \tag{6}$$

where r_1 and r_2 are the inner and outer diameters of the cylindrical LVL, respectively.

When E and L in Eq. (6) are substituted with the experimental values at ratios (L/r_2) of 5, 7, 9, and 11, and when $4L^2/3E(r_2^2 + r_1^2)$ and $4L^2/3(r_2^2 + r_1^2)$ are represented by y and x axes, respectively, the inverse of E' is represented by the gradient of the regression line, as shown in Fig. 12. The modulus of rigidity can be calculated from the intercept of the regression line at the y-axis, which indicates $2.0/G$. This method was applied to only four-ply cylindrical LVL, so further investigation of cylindrical LVL with other ply numbers is needed.

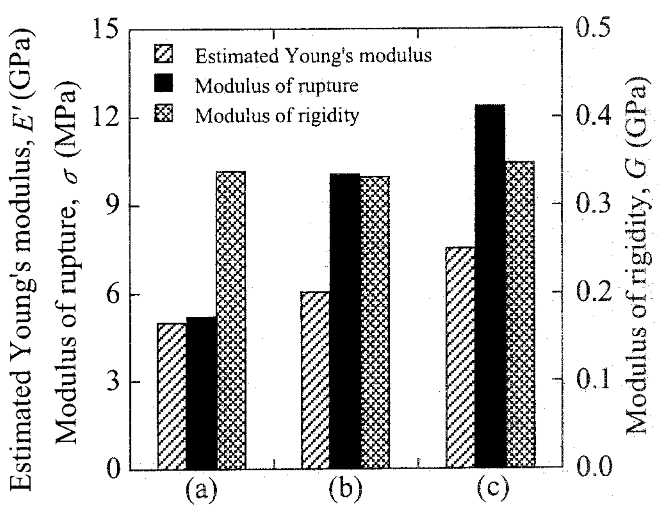

Fig. 13. Comparison of bending performance of cylindrical LVL (four-ply) manufactured by various combinations of veneer width and press time. Refer to Fig. 12 for an explanation of (*a*), (*b*), and (*c*)

Figure 13 compares the bending performances of the four-ply cylindrical LVL samples manufactured by various combinations of veneer width and press time. As indicated by (a) in Fig. 13, the cylindrical LVL manufactured from 45 mm wide veneer and 25:75 DF-1000/D-33 with a press time of 21 s recorded an E' of 5.00 GPa and σ of 5.23 MPa. When the press time or veneer width was increased, higher values of E' and σ were obtained. The E' and σ of the cylindrical LVL manufactured using a combination of 90mm wide veneer tape and 42s press time were 7.55GPa and 12.4MPa, respectively, as shown by (c) in Fig. 13. It could be due to an improvement in the interlaminar bonding as the press time was extended or a reduction in the number of butt joint defects in wider veneer.

Despite using different materials and manufacturing systems, the cylindrical LVL manufactured by Yamauchi et al. recorded moduli of elasticity and rupture of 8.73GPa and 14.8MPa, respectively.[18] In our preliminary study, butt joint free flat lauan LVL (four-ply) manufactured by hot-pressing with a conventional platen hot press at 160°C for 4min using neat D-33 had moduli of elasticity and rupture of 9.78GPa and 126MPa, respectively. However, the values of E' and σ of the cylindrical LVL samples were lower than these values, even when 90mm wide veneer was used with 42s press time. Deformation of the cylindrical LVL manufactured was caused by delamination at the glue-line, and the fracture mode was brittle. One of the possible factors contributing to the low mechanical properties of the cylindrical LVL was insufficient polymerization of resin adhesive during belt-pressing due to the occurrence of pre-cure at the interface of resin and hardener. Furthermore, in this study the distance between adjacent butt joints was more than 16 times[19,20] the veneer thickness. However, there were a number of the butt joints in the span, as the veneer used was thin. Therefore, the presence of higher number of butt joint defects in the span may also affect the bending performance of this cylindrical LVL.

The G of the products were almost constant, at about 0.35GPa, irrespective of the manufacturing conditions. This may be attributed to the similar cross-sectional area of the cylindrical LVL with equal ply number, which contributes to their similar degree of shear resistance.[10]

Conclusions

A new spiral-winder was developed for the continuous manufacturing of structural cylindrical LVL, and an optimum resin mix was identified that met the requirement of a short pressing time in this system. Subsequently, cylindrical LVL were trial-manufactured using the optimum resin mix with various combinations of veneer width and press time; and the mechanical properties were evaluated.

The shortest gelation time was obtained for 25:75 DF-1000/D-33. Temperature had a marked effect on the gelation time of the resin mix, where a gelation time of less than 30s was obtained at above 100°C bath temperature.

Plywood samples manufactured using 25:75 DF-1000/D-33 had dry bonding strengths of 1.1 and 1.3MPa at press temperatures of 80° and 100°C, respectively, despite a pressing time as short as 5s. Both the dry and wet bonding strengths showed a similar trend of variation with respect to changes in resin mix and press temperature.

DF-1000/D-33 in a 25:75 ratio is considered to be the optimum resin mix for the spiral-winder we developed. The mechanical properties, especially the MOR, of the cylindrical LVL need to be improved, either through utilization of wider veneer tape or longer pressing duration.

Acknowledgments The authors thank the members of the Divisions of Structural Function and Wood Composites, Wood Research Institute, Kyoto University. Special thanks are also directed to Dr. Ee Ding Wong for her critical reading of this manuscript, constant support, and constructive suggestions.

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