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STUDY OF COMPRESSED PLYWOOD STRUCTURE AND DENSITY VARIANCES

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ABSTRACT

This paper covers fundamental of simulating the facial textures of reconstituted veneers. Based on the behaviors of plywood under compressive deformation in a single-arc mold, three regions of bottom surface of molded plywood were proposed and their scopes were developed respectively through regressive analysis. The effects of mould geometry on the curved structure and compression rate of molded plywood were investigated, and the molded veneer curvature and density models were established using cubic spline curves. This makes possible to use computers to simulate the reconstitution of fast-growing species as a replacement of naturally rare thin veneers.

KEYWORDS: Artificial thin veneer, curvilinear equation, density variances.

INTRODUCTION

Artificial thin veneer is a new kind of wood-based decorative material with such characteristics as those of natural rare species in texture, grain and color, or as those of art patterns. The new product is manufactured through the following steps: peeling veneers from ordinary or plantation tree species, coloring the veneers, assembling the veneers, molding the assembly and finally slicing or rotary cutting the laminated timbers (Huang et al. 2004). Different processing methods will result in different decorative patterns. Luo et al. (1984) investigated the manufacturing process for artificial thin veneers using hybrid poplar and lauan to imitate rosewood teak. Tang (1998) explored a technique using embossed molds to produce tangential grains by means of compressing multiple plies of veneers. However, in the real production of thin veneers it is hard to meet the needs for grain variety and accuracy. Many trials are thus needed to achieve a target grain pattern, which consumes a lot of time and resources. As known, the curvilinear structure of the molded flitch directly determines the grain pattern of thin veneers, and the density variance of the compressed flitch affects the color of thin veneers. If we can predict the curvilinear equations and density variances of individual plies in the flitch, we can easily simulate the grain pattern of certain peeled veneers using a computer simulation program.

Principally, the compression of multiple layers of veneers is actually a type of plastic molding of wood materials. Misato (1994) proposed a theory of wood deformation and compression resilience in regards to the transverse compression of wood. Sliker (1989) developed an equation of wood structure based on standard specimens and a method for measuring the small Poisson ratio. Although these studies were focused on the simple loading of standard wood specimens, they are still useful references to the proposed study.

The investigations were conducted regarding the curvilinear structure and density variance of molded plywood with multi-plies of veneers compressed in a singular arc mold. The effects of the mold geometry on the compression characteristics of the molded plywood were analyzed, and the veneer curvilinear and relative density prediction models were also established. By so doing, fundamentals were founded in regards to the computer simulation of using fast-growing species to imitate naturally rare species, and the mechanical properties of curved plywood can also be predicted as the basis of similar research.

MATERIAL AND METHODS

Material

Poplar (*Populus×euramericana* (Dode) Guineir cv. *I-72/58*) veneer was obtained from the north area of Jiangsu Province, China. The poplar veneer was used to make curved plywood in a single arc mold. Veneer thickness 1.8-3.5 mm, moisture content 12 %. The steel made arc mold with three curvature radiuses: 17, 24, and 37 mm; and adjustable height: 0-15 mm. Other materials: UF resin with a solid content of 45 %, and arc cauls.

Experimental methods

Poplar based core veneers were cut into a size of 300 × 300 mm, and then its thickness was measured along the diagonal. Nine plies of veneers were assembled into plywood with the resin amount of 150 g.m^{-2} applied on a single face. The nine layers of veneers were marked with 1 to 9 correspondingly, and assembled with veneer grains perpendicular to each other, and then pressed using a mold underneath the assembly. The following pressing conditions were used for the experiment: press temperature 120°C, pressure 0.88 MPa, and press time 1 min.mm^{-1} with a 3-stage pressure reduction process. After cooling down for 14 h, measurements were conducted on selected points. Starting from the symmetrical centre of the sample along the x-axis, measurement points (x_i) were selected individually, the sample was cut through along the selected points one by one, and the sawn surfaces were then planed before surface scanning. The scanned

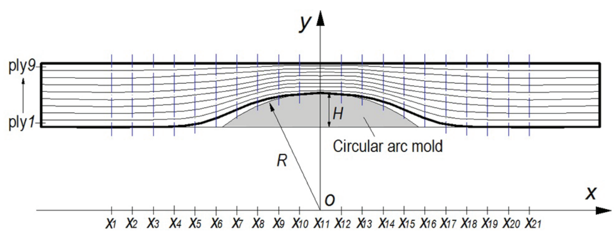

Fig. 1: Diagram of curved molded plywood and measured points.

images were magnified 10 times and measurements were carried out simultaneously using a vernier caliper. The measured data on the section was then reduced by 10 times to obtain the real data on the plane (Fig. 1).

RESULTS AND DISCUSSION

Compression characteristics of multiple plies of veneers

As shown in Fig. 2, the plywood compressed using a singular arc mold demonstrates three distinct regions: *AB*-the abutted region where the mold surface and veneers contact closely for the longest time under the maximum pressure, thus showing the biggest compression rate; *BC*-the transitional region where veneers and mold platen do not contact tightly, veneers being in a status of suspending and compression rate being between *AB* and *CD* sections; *CD*-the flat pressing region where pressure and its direction are not affected by the singular arc mold at all; *B* and *C* are cut-off points between the bottom surface of plywood and mold, and between the bottom surface and the platen.

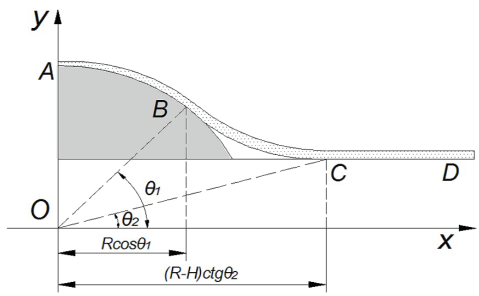

Fig. 2: Three regions of bottom surface of molded plywood.

In order to study the impact degrees of three sections, two new terms are introduced: cut-off angle θ_1 and ce angle θ_2. Their definitions are as shown in Fig. 2: taking the centre of the mold curvature circle as the origin (O) of the rectangular coordinator system, the angle between OB and the x axis is defined as θ_1 and the angle between OC and the x axis as θ_2. θ_1 is used to determine the location where veneers and mold separate, showing the wood rigidity: the stronger the rigidity, the bigger the cut-off angle. θ_2 indicates the wood flexibility: the larger the flexibility, the bigger the angle, and accordingly the veneer is more easily compressed and contacted with the mold.

To simplify the quantification of the geometrical characteristics of the mold, convexity U is defined to establish the relation of the two angles and the mold geometry, and its final calculated result is correlated to the mold geometry.

$$U = H^2/R \tag{1}$$

According to the method introduced in Section 2, three types of molds will be chosen with the dimensions: *R*=17 mm, *H*=11.3 mm; *R*=24 mm, *H*=14.1 mm; and *R*=37 mm, *H*=10.2 mm respectively. Every mold compressed 5 plywoods for actual measurements. The measurements have proved that there exist strong relationships between $\cos\theta_1$ and *U*, and between $(R - H) \cot \theta_2$ - R $\cos \theta_1$ and *H*. By regression analysis, Eq. 2 and an implicit function equation, Eq. 3, have obtained:

$$\cos\theta_1 = 0.028U + 0.435 \tag{2}$$

$$(R - H)\cot\theta_2 - R\cos\theta_1 = 0.344H + 24.749 \tag{3}$$

The coefficients of determination (r^2) for the two equations are 0.9998 and 0.8211 respectively, indicating good fitting results.

Curvilinear equations of bottom surface curvature

Using a common tool for constructing a free curve-piecewise spline curves, curves of individual plies are predicted regarding the plywood compression. The cubic spline curves *S(x)* are cubic polynomial curves, and the expression corresponding to the interval (x_{i-1}, x_i) is:

$$S_i(x) = M_{i-1}\frac{(x_i - x)^3}{6h_i} + M_i\frac{(x - x_{i-1})^3}{6h_i} + (y_{i-1} - \frac{M_{i-1}}{6}h_i^2)\frac{x_i - x}{h_i} + (y_i - \frac{M_i}{6}h_i^2)\frac{x - x_{i-1}}{h_i}, (i = 1, 2, \cdots, n) \tag{4}$$

where: (x_i, y_i) - the coordinate vector of characteristic points,
h_i - the difference vector of abscissa for characteristic points,
$h_i = (x_i - x_{i-1})$,
M_i - the vector of the flexural moment equation,
$\lambda\mu$=G which can be solved from Eq. 5:

$$\begin{bmatrix} 2 & 1 & & & & \\ \mu_1 & 2 & \lambda_1 & & & \\ & \mu_2 & 2 & \lambda_2 & & \\ & & \ddots & \ddots & \ddots & \\ & & & \mu_{n-1} & 2 & \lambda_{n-1} \\ & & & & 1 & 2 \end{bmatrix} \begin{bmatrix} M_0 \\ M_1 \\ M_2 \\ \vdots \\ M_{n-1} \\ M_n \end{bmatrix} = \begin{bmatrix} g_0 \\ g_1 \\ g_2 \\ \vdots \\ g_{n-1} \\ g_n \end{bmatrix} \tag{5}$$

where: $\lambda_i = \dfrac{h_{i+1}}{h_{i+1} + h_i}$; $G_i = \dfrac{6}{h_{i+1} + h_i} \cdot (\dfrac{y_{i+1} - y_i}{h_{i+1}} - \dfrac{y_i - y_{i-1}}{h_i})$.

Due to the symmetry of the molded sectional curves, only the right side bottom curved face is investigated. As mentioned before, the bottom curved face can be divided into three sections. Therefore four characteristic points are used to determine three sectional spline curves. The four characteristic points include peak point *A*, cut-off point *B* between veneers and the mold, cut-off point C between veneers and the platen, and point *D* on the flat-compressing area (Fig. 2).

The position vectors of the four characteristic points can be determined using the fitting formulas of Eq. 2 and Eq. 3. And then, the sectional equations of the bottom curved face can be achieved through substituting the position vectors of the four points into Eq. 4.

By this method, we predicted the bottom curve formed using the arc mold with R=24 mm and H=14.1 mm. The predicted result and the actual curve are observed in Fig. 3.

It is seen from Fig. 3 that there is a good fit between the predicted model *S(x)* and the actual curve *f(x)* as per veneer compression, particularly in the circular section of the abutted region and the linear section of the flat pressing. However, the difference is mainly observed in the free compression region. The main reason is because the differences between the predicted vector and actual vector are accumulated and reflected in the spline curves, and because the second directive of *S*(*x*) grows slowly after the inflexion, leading to a flatter predicted curve compared to the actual

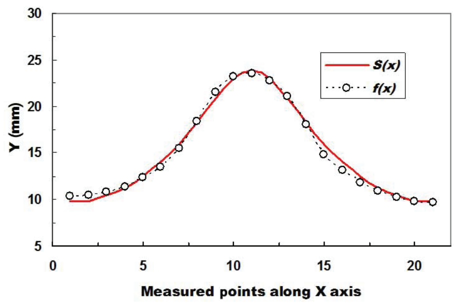

Fig. 3: Comparison of predicted and actual bottom curves of molded plywood.

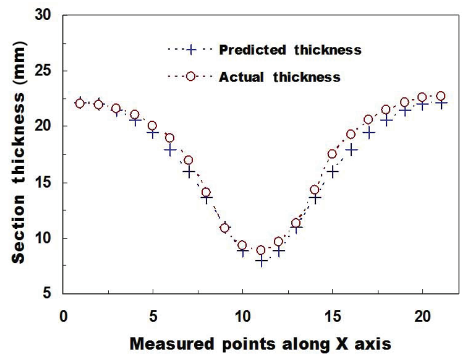

Fig. 4: Comparison of predicted and actual thickness of curved surface.

curve. Nevertheless, the above error is completely acceptable in engineering.

Thickness predictions

Since plywood thickness is much smaller than width and length, the compression process can thus be simplified and only the thickness change is considered for modeling. Hence, the density profile can be solved using the thickness compression rate T_v, as shown as below:

$$T_v = \frac{t_o - t}{t_o} \tag{6}$$

where: t_o - the initial thickness of plywood (mm),
t - the thickness after compression (mm).

Assuming veneer is a power-level reinforced material considering its inborn characteristics, and its compression rate (thickness change) has the following relationship with pressure (Kollmann 1968): $T_v=aP^n$, P—unit pressure for hot pressing (MPa). Lu et al. (2002) obtained the veneer compression rate after a large amount of testing: $Tv=0.13P^{0.85}$ ($0.5<P<4.5$), which considered both the spring back after unloading of plywood and the thickness change after 24 hour lay-up. Therefore, the total thickness (flat compressed portion) after compression can be solved using the following formula if the thicknesses of individual plies are known:

$$t = (1 - Tv)t_0 = (1 - 0.13P^{0.85})t_0 \tag{7}$$

The bottom surface curve of the arc mold can be calculated using the prediction model of plywood curvature, and the thickness equation can thus be derived through a simple conversion of coordinate axes:

$$t(x) = t + (R - H) - S(x) \tag{8}$$

Substituting Eq. (7) for t into Eq. (8) gives the thickness equation of curved compressed plywood. Additionally, the curvilinear equation of any ply of veneer is obtainable based on the Eq. (8). For example, assuming the characteristics of individual plies are the same, then the thickness of compressed individual plies will be $t(x)/n$ (n—number of plies). The coordinate vectors of the four characteristic points in any m^{th} ply can be solved using the cumulative method.

Fig. 4 compares the predicted thickness with the actual thickness of the curved surface, which shows that the predicted total thickness of plywood (i.e. the thickness of the flat compressed region) is 21.99 mm and the actual measurement is 22.50 mm, generating a deviation of 2.3 %: the prediction is obviously accurate. In contrast, the actual thickness of the transitional and abutted regions is larger than the predicted thickness owing to:

1. The free compression section of the spline has shown a higher predicted parameter S(x) in comparison to the actual measurement, and accordingly the region demonstrates the lower predicted thickness.
2. The compression rate of the abutted region is the biggest among all regions thus leading to a larger spring back after unloading. In addition, the fitting formula for the compression rate (Eq. 7) could not reflect adequate accuracy under the conditions of lower mat pressure and smaller veneer thickness. The prediction deviation gradually increases with the increase of mat pressure and veneer thickness. The deviation between the predicted and actual thicknesses is -0.12-1.58 mm, i.e. -1.17-9.98 %; therefore, it is completely feasible to predict the thickness of curved plywood using Eq. 8.

Density predictions

Assuming the initial veneer density is one unit, then the relative veneer density after compression, D, will be: $D=t_o.t^{-1}$. Therefore, the relative density equation of curved plywood can then be solved using the thickness equation of the curved surface:

$$D(x) = Dt / t(x) = t_o .\ t^{-1}(x) \qquad (9)$$

Assuming the individual plies have the same characteristics, that is, the compression rates of individual veneers are equal to the total compression rate of the compression section. In this case, the relative density of the individual plies is correspondingly equal to that of the compressed section.

Fig. 5 shows the difference between predicted and actual relative density distribution for the central layer of compressed plywood. The relative density of individual plies indicated a different distribution from that of the total relative density in regards to the data discreteness and jumpiness. The main reason may come from the variability of inborn wood characteristics. It is found after observations of the three regions that the veneer density shows less fluctuation in

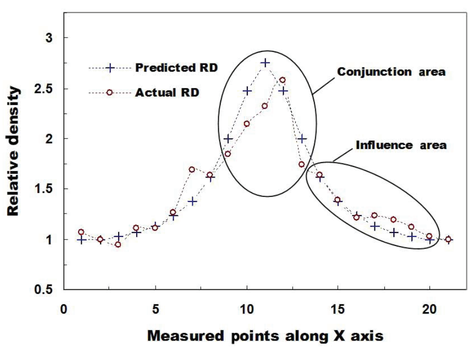

Fig. 5: Predicted and actual relative density (RD) distribution for the central layer of curvature.

the flat compression and transitional regions, thus the predicted density is generally acceptable. However, a big difference is identified between the predicted and actual density distribution in the abutted region due to a larger compression rate existing in the abutted region, which may cause the damage owing to the inborn defects and poor compression strength of some veneers; meanwhile, other veneers with higher compression strength can not receive enough compression, hence leading to deviated density distributions as shown in Fig. 5.

Overall, many factors can influence the curve shape, thickness and density variances of the curved molded plywood. Hence, it is very complex and difficult to predict these parameters exactly, and no related study has been reported so far. This research is a new attempt which may offer some fundamentals and references in regards to the characteristics of curved molded plywood and the simulations of reconstituted veneers.

CONCLUSIONS

This study focuses on fundamentals of compressive deformation of individual plies under the single arc molding process while proposing two concepts: Cut-off angle and ce angle, and developing the equations for the abutted and transitional regions through regressive analysis. The effects of mold geometry on the curved structure and compression rate of molded plywood were investigated, and the molded veneer curvature, thickness and density models were established using cubic spline curves which provide the basis for the simulation and manufacture of naturally rare veneers using fast-growing species. The parameters for the validation of the models were obtained from a large amount of experiments, and thus have a higher accuracy. The actual data in general fitted the predicted data quite well, which proved the validity of the methodology used in the study and the accuracy of the predicted models derived from this research.

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