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CHIPLESS MACHINING: CHALLENGES IN MANUFACTURE OF LAMINATED VENEER PRODUCTS

Lars Blomqvist[1], Sven Berg[2], Dick Sandberg[2]

[1] Linnaeus University, Forestry and Wood Technology,
SE-351 95 VÄXJÖ, SWEDEN
lars.blomqvist@lnu.se
[2] Luleå University of Technology, Wood Science and Engineering
SE-931 87 SKELLEFTEÅ, SWEDEN
sven.berg@ltu.se, dick.sandberg@ltu.se

ABSTRACT

A laminated veneer product (LVP) consists of veneers bonded together with adhesive under pressure into a predetermined shape and, in general, under increased temperature to shorten the curing time of the adhesive. The process is commonly used in furniture design to manufacture complex forms such as thin shells. In the industrial production of LVP and when the ready-for-use components are exposed to climate variations, rejection due to distortion of the laminates is a major problem. The shape stability depends on a variety of material and process parameters, and this study has focused on the influence of fibre deviation in a single veneer. Recent research on the shape stability of LVP and how distortion is influenced by various material and production parameters is presented. A finite-element model for LVP is introduced and the use of this model is exemplified by predicting the shape of a LVP with fibre distortion in a single veneer. The results show that it is possible to improve the shape stability of LVP if knowledge of various material and process parameters is implemented in the manufacturing process, and that a simulation based on a model of the wood material can be helpful in estimating the risk of an undesired deformation of the product.

Keywords: finite element modelling, shape stability

INTRODUCTION

Laminated veneer products (LVP) have been used in countless applications throughout the ages, e.g. in furniture, boats, aeroplanes, components of various utility items, and sports equipment. Today, the main applications of laminated veneer products are as components for furniture and interior design. The method has had a great success around the world as shown by the examples of chairs from Denmark and Sweden in Figure 1.

The advantages of laminated veneer over solid wood and many other materials are:

- high strength and at the same time low weight,
- extensive possibilities of producing a design that is beyond what would be possible with solid wood, and
- the possibility of an efficient manufacturing process.

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a) b) c) d)

Figure 1: Chairs including ready-for-use components of LVP and the designer, marketing company, and the estimated total number of produced items since its introduction on the market. a) "Seven" [Arne Jacobsen, Fritz Hansen Ltd., 1955, 5 million], b) "Lamino" [Yngve Ekström, Swedese Ltd., 1956, 250 000], c) "Poäng" or "Poem" [Noburo Nakamuro, IKEA of Sweden Ltd., 1977, >60 million], and d) "Campus" [Johannes Foersom and Peter Hiort-Lorenzen, Lammhults Möbel Ltd., 1992, >1 million] (1).

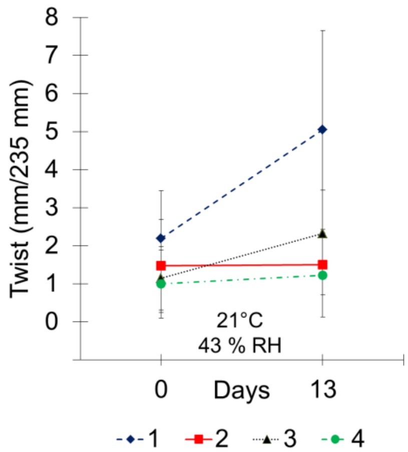
In the industrial production of LVP, rejection due to distortion of the laminated components during manufacture causes a problem. Distortion may also arise later when the products are exposed to climate variations e.g. in use. Distortion and poor shape stability result in increased processing costs, problems with the assembly of components, dissatisfied customers and lower profits.

The purpose of this paper is to provide an overview of recent research on the shape stability of LVP and how distortion is influenced by some material and production parameters, and to illustrate how finite element analysis can be a powerful tool for the prediction of distortion.

DISTORTION OF LVP DURING MANUFACTURE AND IN USE

It is well known that the main reason for distortion in LVP is stresses due to the forming process and to swelling and shrinkage, i.e. deformation of the veneers through moulding, swelling and shrinkage caused by moisture added or released from the adhesive and its curing or from the surroundings in general (2). When these in-built stresses are released, the LVP distorts. After moulding, there is always an instant elastic distortion called spring-back. Spring-back has been well studied and there is in general a good understanding in the industry of how to handle this type of distortion to reach the desired final shape of the LVP, but distortion occurring after moulding has been less studied. In this case, the moisture variation in the LVP, which leads to the release of stresses and to a swelling and shrinkage of the wood material, is of vital importance. Finally, the "principle of symmetry" means that structure of the LVP should be built up symmetrically in the thickness direction of the LVP with respect to number, thickness, fibre orientation and moisture content etc. of the veneers. Following the principle of symmetry prevents distortion and has the following conditions: a) on each side of the *centre veneer* there must be the same number of veneers, i.e. the number of veneers in the construction must always be odd (the "centre veneer" can consist of two veneers if these veneers have properties such that they can be considered to be a single veneer when they are glued together); b) for each veneer on one side of the centre veneer there must be a corresponding veneer in the same relative position on the opposite side of the centre veneer, both being of the same thickness and the same species, having the same moisture content and, preferably, being cut in the same manner; and c) the fibre orientations of the two veneers at the same distance from the centre veneer must run in the same direction. The reason for choosing this design is primarily the phenomenon of shrinkage and swelling of wood. Due to the great difference between the shrinkage and swelling parallel to the fibres and perpendicular to the fibres, stresses will always arise or be released in LVP when the moisture content changes. It is of course possible to find other combinations of veneers that will result in a stable laminate or LVP, but even in these cases the inbuilt stresses must be balanced when the product is exposed to a moisture variation.

To take this semi-theoretical description to a more practical level, we can study what happens when the moisture contents of the veneers are not the same before moulding of a LVP, Figure 2. For simplicity in this presentation, only twisting of the product is presented, but for more detailed information about the studies the publications referred to are recommended. The products were a 3D-shaped seat shell, built-up of symmetrically 7 cross-laminated veneers of birch (*Betula pubescence* Ehrh.), with different moisture content patterns in the different veneers.



Orientation of lengthwise (L) and transverse (T) veneers seen from "front to back" are L_1-T_2-L_3-T_4-L_5-T_6-L_7

Group No.	Moisture content (MC) of single veneers before moulding
1	3 veneers with 19 % MC (L_1, T_2 and L_3) and 4 with 5% MC
2	1 veneer (L_1) with 19 % MC and 6 with 5% MC
3	5 veneers with 4% MC veneers (L_1 and L_7) with MC 7 %
4	Reference, 5% MC in all veneers

Figure 2: Mean values and standard deviation of twist immediately after pressing and after two weeks of storage (3). The seat shells of birch were made of peeled veneers with different moisture contents exposed to a constant climate.

Immediately after moulding, there was no significant difference in twist between the different groups (mean values from 15 or 30 shells in each group). After 13 days of conditioning at the production site at an almost constant relative humidity and temperature, the seat shells with the greatest MC difference between veneers before moulding exhibited a substantial increase in twist, i.e. poor shape stability. The shells with all the veneers at the same moisture content or only the outermost veneers at a higher moisture content showed only a moderate change in twist on storage.

The results indicate that, if the veneers are well-conditioned before moulding, i.e. have a low and even moisture content, the distortion of the moulded assembly in use is reduced. A high moisture content in the outermost veneers of the assembly before moulding did not influence the behaviour to any great extent, probably due to the drying of these veneers during moulding. A high moisture content in some of the veneers can lead to considerable distortion of the product after moulding, especially if the moisture content is asymmetrically distributed.

Most of the adhesives used for LVP contain a lot of water that increases, at least immediately the MC of the veneers. Figure 3 shows the twist in a 3D-shaped furniture seat shell of birch where the adhesive was distributed unevenly on the veneers to give an uneven moisture distribution in the veneers before moulding. In this study, the initial MC of the well-conditioned veneers was 5%,

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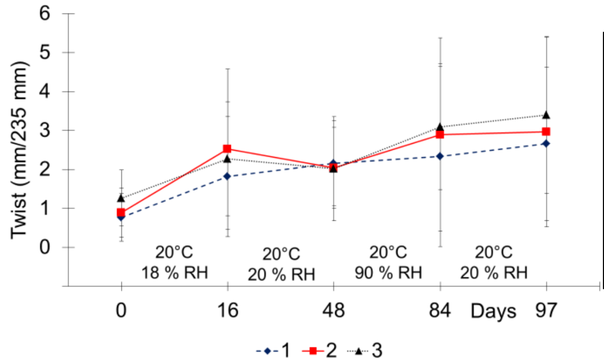


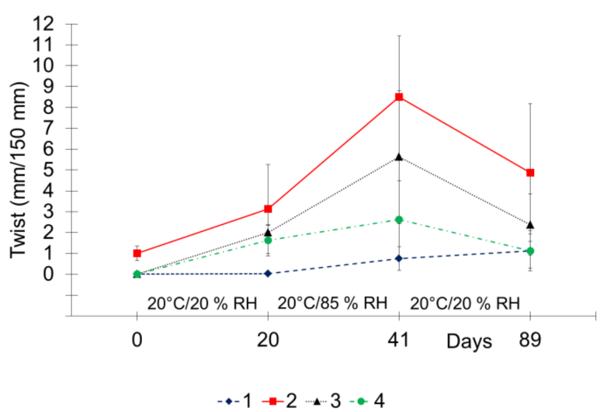
Orientation of lengthwise (L) and transverse (T) veneers seen from "front to back": L-L-T-L-T-L-T-L-L

Group No.	**Moisture content (MC) of single veneers**
1	Reference (even adhesive distribution)
2	25 % extra adhesive applied diagonally
3	25 % extra adhesive applied on the left side

Figure 3: Mean values and standard deviation of twist immediately after pressing and during relative humidity cycling (3). The seat shells were manufactured of peeled birch veneers and had an uneven adhesive distribution on the veneers before moulding.

and the added moisture from the adhesive increased the mean MC of the veneers by about 4 percentage points. After moulding, the shells were exposed to relative humidity (RH) cycles to accelerate the distortion, and it can be concluded that an uneven adhesive distribution had little or no influence on twist, since the differences in MC within and between the veneers were low. In contrast, the uneven adhesive distribution on the veneer before moulding did affect the level of spring-back.

Since most LVPs are manufactured from peeled (rotary-cut) veneers it is also of interest to understand of how the orientation of individual veneers in the laminate, i.e. orientation according to fibre orientation and orientation of the loose side (the side with "lathe checks") or the tight side of the veneer, affects the shape stability. Figure 4 shows the twist of a flat three-ply laminated veneer based on peeled veneers of beech (*Fagus sylvatica* L.) with dimensions 3.6 × 150 × 150 mm (thickness × width × length). Four types of laminate were studied: loose sides of all veneers in the same direction (perpendicular to and parallel to the centre veneer), and loose sides of the outer veneers facing inwards (perpendicular to and parallel to the centre veneer). Four replicates of each type yielded 16 samples.



Orientation of the three-ply veneers.

Group No.	**Orientation of loose side Top**	**Middle**	**Bottom**	**In-plane fibre orientat.**
1	Down	Down	Down	Cross-wise
2	Down	Down	Down	parallel
3	Down	Down	Up	parallel
4	Down	Down	Up	Cross-wise

Figure 4: Mean values and standard deviation of twist immediately after pressing and during relative humidity cycling at 20°C for laminates of beech (4). The orientation of the loose side of veneers was down/up and indicates the relative orientation of the loose side seen from the top of the laminate. Cross-wise (L-T-L) and parallel (L-L-L) fibre orientation of veneers in the laminate.

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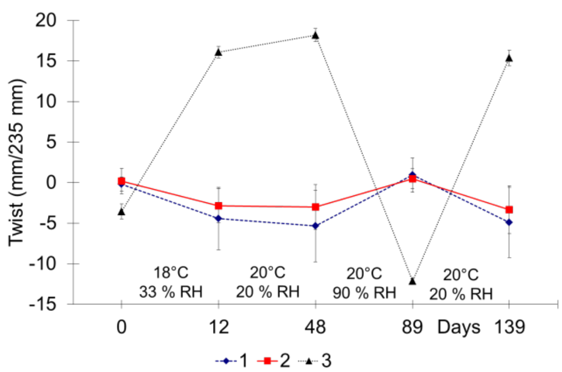
Twist was, as expected, influenced by the veneer orientation. Laminations with the middle veneer perpendicular to the top and bottom veneer (cross-laminated) showed the best shape stability, especially when the loose sides of the veneers were oriented in the same direction. In parallel-laminated veneers, the laminates with opposite directions of the loose sides in the two outermost veneers showed the best shape stability. The major explanation of the behaviour of the laminates with respect to loose/tight side is that the loose side expanded more than the tight side going from the dry to the humid climate.

In sawn timber, twist is mainly a consequence of a deviation in fibre orientation from the main direction of the sawn product, and this is also true for LVP. Figure 5 shows twist for the same type of seat shell that was tested with respect to variation of MC (see Figure 2 and 3), but here the MC was constant and the fibre orientation varied. Twist was low directly after moulding, but when the moulded product was subjected to variations in RH, the twist increased considerably with different fibre orientations in the assembly. For the specific product used in this study, a twist of less than 3 mm/235 mm means that the seat shell is accepted for further processing. In the case of the shells with the outer veneers orientated 5 degrees in opposite directions (group 3) the twist increased dramatically during moisture cycling and the product was not accepted for further processing.



Orientation of lengthwise (L) and transverse (T) veneers seen from "front to back" are L_1-T_2-L_3-T_4-T_5-L_6-T_7-L_8

Group No.	**Moisture content (MC) of single veneers**
1	Irregular fibre structure in T veneers
2	Reference, no deviation in fibre orientation
3	Divergent fibre orientation in veneer L_1= +5°

Figure 5: Mean values and standard deviations of twist immediately after moulding and during relative humidity cycling (3). The product was a beech seat shell manufactured with veneers with different fibre orientations.

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MODELLING OF SHAPE STABILITY

In order to study how the design of the LVP and material properties influence the shape stability on exposure to cyclic RH, a FE-model was developed and validated by comparing the results of the model with the results of an experimental study on a moulded laminate.

Experimental study

A 3.6 mm thick moulded laminate of birch (*Betula pubescence* Ehrh.) was manufactured and tested for shape stability on exposure to cyclic RH, Figure 6. Defect-free rotary-cut veneer with a thickness of 0.6 mm was used, and the surface veneers were sanded to a thickness of 0.4 mm before moulding. The veneers were cut to dimensions of 400 x 660 mm (lengthwise veneers) or 660 x 400 mm (transverse veneers) depending on the orientation which the veneers should have in the laminate.

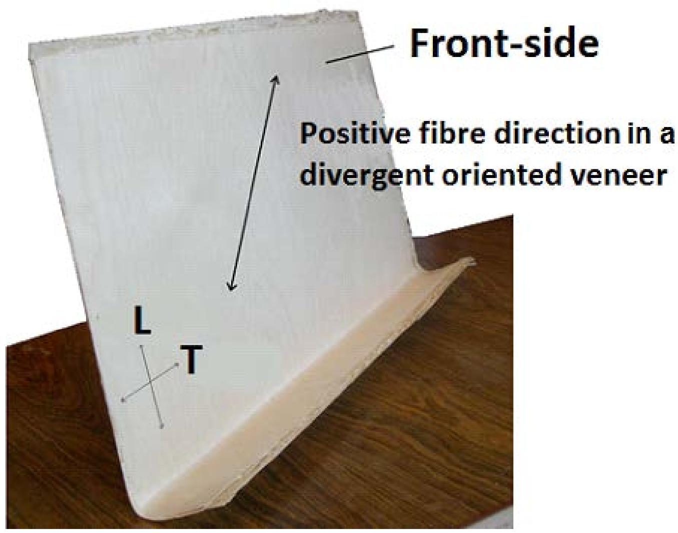


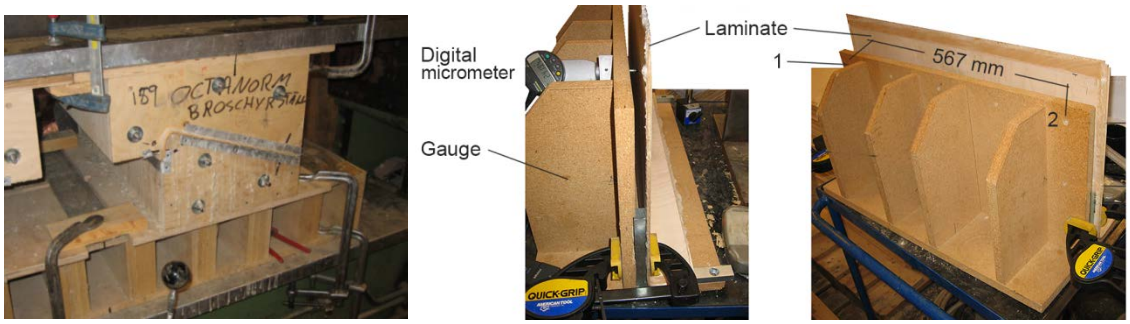
Figure 6: The studied laminate with the different definitions used. The laminate was 400 mm in the length (L) and 660 mm in width (T). The total thickness was after moulding 3.6 mm.

The fibre orientation of the lengthwise veneers was either straight or at an inclination of 7 degrees relative to the L-direction of the laminate (see Figure 6). The transverse veneers were all straight grained. The veneers were conditioned at 20ºC and 20% RH to an equilibrium moisture content of 4.5% before moulding. A laminate consisted of 7 veneers and a total of two groups consisting of 15 laminates with different relative veneer orientations as shown in Table 1 were moulded.

Table 1: Orientation of veneer within the laminate for the test groups seen from front (L1) to back (L7) of the laminate (Figure 6). Veneer no. L7 in group no. 2 is with divergent fibre orientation.

Group No.	Veneer with divergent fibre orientation in the laminate	Placement of veneers in the laminate
1	-	L_1–T_2–L_3–T_4–L_5– T_6–L_7
2	L_7=+7°	L_1–T_2–L_3–T_4–L_5– T_6–L_7

The laminates were moulded in a high-frequency (HF) heated tool, Figure 7a. A urea-formaldehyde (UF) adhesive system (Casco Adhesives Inc., resin part 1274 and hardener 2584) was used, and 100 g/m^2 of adhesive was spread on each side of the transverse veneers. The total press time was about 4 minutes, of which 1 minute was HF-heating to reach a temperature of about 110°C in the inner bond-line. The mean applied surface pressure was 0.5 MPa. After moulding, the laminates were freely placed in up-right position and allowed to cool.



a) b)

Figure 7: Moulding and measurement of twist of a laminate: a) pressing tool in which the laminates were moulded, and b) determination of twist for a laminate (left) and the measurement locations on the gauge (1 and 2) where the distance between the gauge and the laminate was measured with the help of a digital micrometer.

The laminates were then moved to a climate chamber where they were exposed to different RH levels at constant temperature, Table 2. The twist of the laminates was measured with help of a gauge and a digital micrometer at two locations on the laminate, Figure 7b. *Twist* was defined as the difference in distance between the laminate and the gauge in locations 1 and 2 in Figure 7b. The elastic recovery (spring-back) after moulding was not included in the study.

Table 2: Climate conditions where the laminates were stored during the RH cycles. EMC – equilibrium moisture content at the given climate.

Total time (days)	Time in climate (days)	Climate before measurement of twist (EMC)
0	0	Directly after moulding excluded spring-back
41	41	20°C/20% RH (4.5%)
89	48	20°C/90% RH (21%)
103	14	20°C/20% RH (4.5%)

FE-analysis

The twist of the laminate was studied with the aid of a three-dimensional static finite element model (FEM) for small deformations. The analysis considers the material behaviour when the veneers were glued together to form a laminate with an EMC of 4.5%, and with the same design, definition of twist and RH exposure as for the laminates in the experimental study (see Table 1 and 2).

A standard FE code (ABAQUS 12.2) complemented with a user-defined material subroutine of the constitutive model was used. The material model used an orthotropic model that takes into account the moisture-temperature and mechanical behaviour of the wood material (5). The FE-model was 3-D and had reduced integration elements. The total strain rate was assumed to be the sum of the elastic strain rate ($\dot{\varepsilon}_e$), the moisture-induced strain rate ($\dot{\varepsilon}_w$) and the mechano-sorptive strain rate ($\dot{\varepsilon}_{w\sigma}$):

$$\dot{\varepsilon} = \dot{\varepsilon}_e + \dot{\varepsilon}_w + \dot{\varepsilon}_{w\sigma} \quad (1)$$

The stiffness parameters used in the simulations were based on data presented by Dinwoodie (6) for birch wood, the shrinkage parameters were for birch data presented in (7), and since mechano-sorption data are limited for birch, the values used were based on data presented in (8) for Norway spruce.

The laminate boundary conditions were set to restricted rigid-body motions and the bond-lines between the veneers were modelled under tied constraint conditions. The moisture variations were assumed to be homogeneous during the conditioning time for all the veneers.

The influence of temperature and moisture content on the stiffness properties was based on relations presented in Ekevad (2006).

Table 3: Elastic parameters (6), shrinkage parameters (7), and mechano-sorption parameters (8) used in the simulation. The subscripts L, R and T in the table represent the longitudinal, radial and tangential fibre directions in the wood.

Elastic parameters	E_L (MPa)	E_R (MPa)	E_T (MPa)	G_{RL} (MPa)	G_{TL} (MPa)	G_{RT} (MPa)	ν_{RT}	ν_{LT}	ν_{RT}
	16300	1100	570	1160	680	66	0.68	0.038	0.015
Shrinkage parameters	α_L	α_R	α_T						
	0.013	0.133	0.256						
Mechano-sorption parameters	M_L (MPa-1)	M_R (MPa-1)	M_T (MPa-1)	M_{LR} (MPa-1)	M_{LT} (MPa-1)	M_{RT} (MPa-1)			
	0.1·10-3	0.15	0.20	0.008	0.008	0.8			

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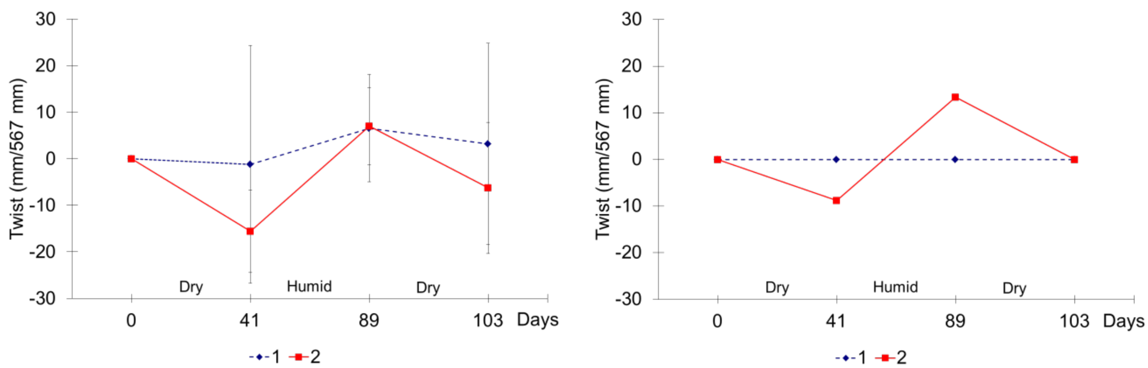
RESULTS AND DISCUSSION

Figure 8 shows the twist of the laminates determined by the experimental study and by the FE study. After moulding, twist is almost non-existent in all the laminates, regardless of fibre orientation in the veneers. This is also the result of the FE analysis. In the experimental study, the exposure the cyclic RH results in an increasing and variable twist in both groups of laminates. The twist varies to a great extent between individual laminates, which indicates a large variation in material properties and/or properties of the laminates related to the manufacturing process. The twist in laminates with only straight-grained veneers (group 1) was however much less than the twist in the laminates with fibre deviation.

The FE analysis gave in no twist during RH cycles for laminates with straight-grained veneers, and a twist similar to that found in the experimental study for laminates with fibre deviation. This indicates the importance of straight-grained veneers to reduce the twist of LVP, but in practice it may be difficult to achieve such conditions since most veneers are not totally straight-grained and during assembly the relative orientation between veneers can be disrupted resulting in a "fibre deviation effect" even if the veneers are straight-grained.



a) b)

Figure 8: Twist in laminates during RH cycles from (a) experimental and (b) FE studies. (a) Mean values and standard deviation of twist in 15 laminates of each group in the experimental study, and (b) the FE analysis of laminates the same design. 1 and 2 are groups according to Table 1.

CONCLUSIONS

In this study, some key factors for poor shape stability of laminated veneer products (LVP) were presented and analysed further with the help of finite element (FE) analysis. When the twist of a LVP is concerned, the relative fibre orientation between the veneers in the laminate is of great importance. This is especially true when the LVP is exposed to a climate that lead to a moisture content variation, and when the principle of symmetry is not followed in the design of the product.

FE analysis can be a powerful tool for predicting the shape of a LVP after moulding, and also during the design stage of LVP to improve the industrial production process and the final product. The FE model presented here shows a good agreement with experimental results, but improvements in material property data as well as the inclusion of the moulding step in the model could be desirable for better agreement.

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