

Textile reinforcement of multidimensional formable wood

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Abstract The thermo-mechanical densification of wood leads to new material characteristics with a plasticity of more than 50 %. The compression process can be influenced by different material and process parameters. By subsequent thermo-hydro-mechanical forming, production of three-dimensional structures is viable. Additional textile reinforcement can increase the formability of partly densified wood structures transverse to the fibre direction. At the same time, the strain will be limited in order to avert premature local failure in the densified wood cell structure. Forming tests confirm the significant increase in drapability by jute and glass fibre reinforcement. Swelling pressure tests were carried out on three densified wood species to determine the internal stresses of the glue line. Thereby, lower compression stresses in poplar (*Populus nigra* L.) than in lime (*Tilia cordata* Mill.) or pine (*Pinus silvestris* L.) were measured. Compression stresses correlate with the density and will increase at higher densification. Furthermore, the determination of local deformation caused by densification and moulding was to be evaluated. The tests were performed by measurement of recovery during water storage using grid strain analysis. Specimens with lower process temperature (75 °C) and high degree of densification (50 %) were less homogeneously deformed than samples at high temperatures (125 °C). In summary, moulding optimised, biaxially densified end grain boards with textile

reinforcement (jute) should be preferably used for technical applications such as interior fitting or the use in automotive engineering.

1 Introduction

Wood can be modified to become mouldable by means of a variety of processes (Kollmann 1936). Bend forming of wood can be used by compression applied longitudinal to the fibre and by densification transverse to the fibre (Haller and Wehsener 2004; Welzbacher et al. 2008; Nairn 2006). Furthermore, it can also be pressed thermo-mechanically and formed hydro-thermo-mechanically in a second process step (Wehsener and Haller 2011; Sandberg et al. 2013).

Three-dimensional moulding takes place on biaxially densified end grain boards. They are produced in the first process from separately compressed square-sawn timber. After this, blocks are glued and end grain boards sliced. During a second process step, the plasticized end grain boards are hydro-thermo-mechanically formed according to DIN 8580 under simultaneous volume change. After the moulding, the fixation takes place as the third step, affected by cooling and drying without any additives (Inoue et al. 2008; Ando and Onda 1999). After previous compression, moulding is realised with more than 50 % elongation. Poplar end grain boards are characterized by low weight, high degree of deformation and low bending strength perpendicular to the panel surface. Determination of the smallest permissible bending radius is calculated with grid strain analysis (GSA), and mechanical properties are determined in Forming Limit Diagram (FLD). The aim of the densification of wood is the creation of homogeneously distributed strain reserves. Different material and process conditions influence the biaxial recovery.

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The stress and strain of the glue line increase by heat and water treatment at the same time. Inhomogeneous densification leads to discontinuous strain. Determination of the inner stress of the glue line has been performed by swelling pressure tests. The worst case of manufacturing end grain boards occurred when joining a low densified part of wood with a highly compressed one. Cracks can appear in the wood lateral or in the glue line.

Application of textile reinforcement to mouldable end grain boards can be used for manufacturing complex wooden components. By applying textile reinforcement structures, designed according to demand, to these spatially formed construction elements on the basis of wood using thermoset resin systems, their load-bearing capacity can be increased significantly, even in critical situations. When reinforcement textiles on the basis of natural fibre such as flax, hemp and jute, combined with biopolymer resin systems designed according to demand with respect to engineering points of view, are used, composite materials on the basis of different renewable resources are created.

The manufacture and processing of natural textile fibres require high quality standards of the raw material. With strain of approximately 10 %, textile reinforcement influences the moulding itself and as such subsequent functional properties of the component. Assessment of the influence of textile reinforcement was carried out in drape tests and applied to textile reinforced end grain components.

2 Methods and processes

2.1 Operating principles and processes of mouldable end grain boards

The deformation of wood is a prerequisite for the generation of mouldable end grain boards. It is carried out by pressure deformation in an open system at increasing temperature (from 80 to 160 °C) and moisture content in wood (from 6 to 18 %). Depending on the initial material, the desired degree of densification, the applied compression process and the chosen process parameters, densification can be carried out uni- or biaxially using pressurization

(3–10 MPa). Usually, conventional hot presses with force and path control are used which can affect the material and process parameters of the final product. Further descriptions of the densification of hardwood can be found in Kollmann (1936) and Vorreiter (1958). The suitability of softwood for densification has been documented by Tanahashi (1990), Ito et al. (1998), Haller and Wehsener (2004), Navi and Sandberg (2012), Sandberg et al. (2013), etc. The uni- and biaxial densification transverse to the fiber starts with buckling of the cell walls until the cell lumina are partly or entirely closed in the early wood and late wood. During the densification process in a conventional hot press, the subsequent three process steps were carried out:

1. heating of the wood
2. application of pressure
3. conditioning and re-cooling

The biaxial densification of squared-timber was carried out using a newly developed compression device. Two interlocking metal plates transform a continuous uniaxial closing motion into quasi-biaxial compression movement. The densification process is completed by the removal of the compression device. Normally, during the load removal, a more or less strong and time-dependent spring-back of the densified material occurs. All phases of the densification and the spring-back are elements of the compression-set-recovery (C_R) and form the modified initial material for the subsequent wood deformation. After the individual woods had been densified they were planed, glued and cut into plates using a blocking procedure (Fig. 1). Depending on the further use, the textile structure was applied using a one-component PUR-resin and a pressure of 0.5 N/mm².

The non-cutting deformation of solid wood is almost impossible because of its low plasticity. The necessary material characteristics with a fracture strain of up to 50 % were realized by a thermo-mechanic densification. Subsequently, wood can be integrated as a visco-elastic polymer into a controllable deformation process. Here, several process conditions, such as deformation degree, stress distribution, load application, shape geometry, size of the workpiece and material characteristics, have an immense impact on the deformation result.

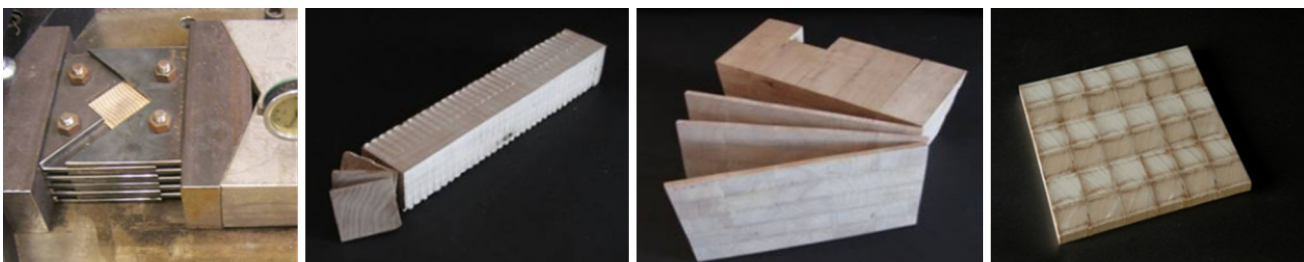


Fig. 1 Production process for end grain boards: (from left) densification device, densified squared timber, glued block and sliced end grain board

During moulding, the following processes take place: The voids are reduced by the pressure tension on the concave side, and the cell walls are folded. On the convex side, the cells stretch and then fail in the end. The relation of pressure and tensile stiffness determines the formation of the neutral line, and in dependence of the breaking strength, failure is determined. Densified wood and subsequent plasticization serve for the increase of the strainability. The combination of wood and textile structures in sandwich elements reduces the tensile stress occurring during moulding to a forced maximum. With respect to the strains, the folded cell walls are stretched apart and the voids are reopened. On the opposite side, voids are closed by compressing. In dependence of tensile strength and pressure, the cells are deformed (Fig. 2). The non-cutting moulding of solid wood transverse to the fibre can be structured as follows after densification:

1. plasticization
2. deformation
3. stabilization

2.2 Operating principles and processes of textile reinforcement structures

When choosing the material, focus was put on the fact that the reinforcement of the wood component has to be

realized almost entirely by biologically renewable resources to develop an almost CO₂-neutral, recyclable composite component. In order to be able to estimate the potential of the new wood-fibre plastic composite and at the same time make the process more attractive for applications with higher performance requirements, glass fibre yarns were integrated parallel to the production of reinforcement structures. The second reason was the different strain between natural fibres (8–10 %) and glass fibre (1–3 %) used in textile structures. Furthermore, to increase the elasticity of the complexly formed wood components during the moulding, textile structures are applied to the wood components for the purpose of load transfer and stress distribution.

For the textile reinforcement of twice-bent, convex forms made of wood, the selection of suitable semi-finished textile products according to demand plays an important role.

For the production of textile reinforcement structures, three surface-forming processes with different characteristics are available, all of which are mainly used for the production of highly loadable continuous fibre-reinforced composites:

- the stitch-bonding technique (e.g., uni-, bi- or multi-axial integration of reinforcing threads possible),
- the weaving technique (e.g., multi-layered weaving structures with biaxial reinforcement) and
- the flat knitting technique (e.g., highly drapeable reinforcement structures with mono-, bi- or multi-axial reinforcement, 3D-shaping possibilities).

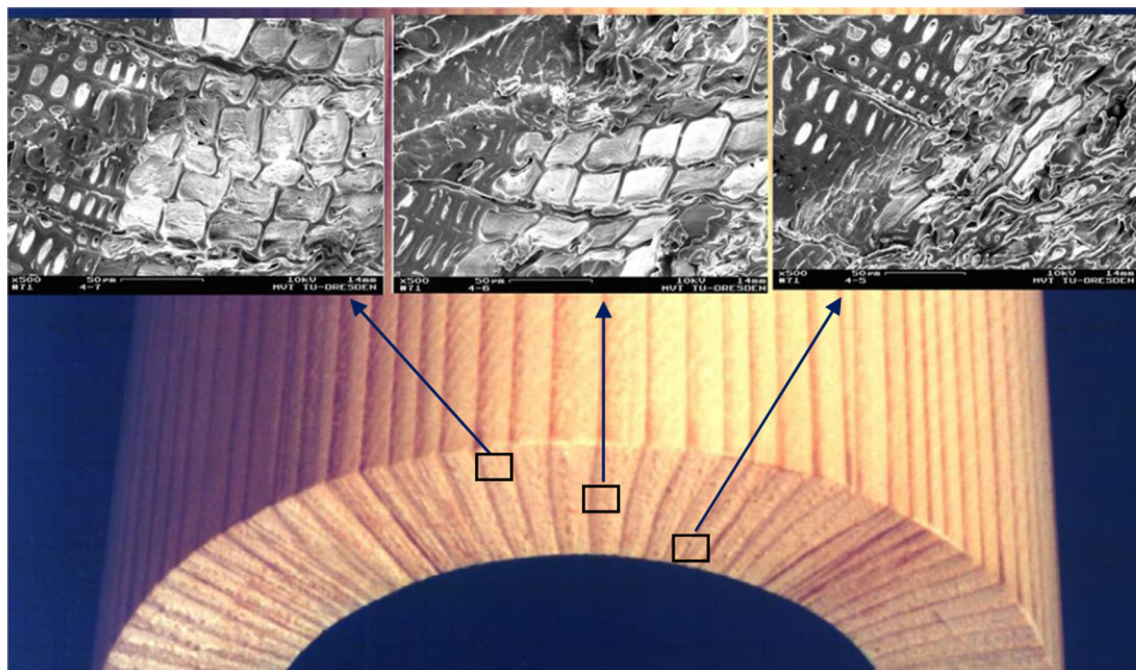


Fig. 2 Densified pine wood after uniaxial moulding (deformation status from *left to right*: outside—tensile strain, middle—neutral, inside—deformation by compression)

Table 1 Material parameters of processed yarn, wet and dry

| Yarn type | Yarn count Tt (tex) | Condition | Maximum tensile force F_{\max} (N) | Maximum tensile force strain ε (%) | Force-E- module E (GPa) | Maximum tensile force to yarn count F_{Tt} (cN/tex) |
|---|------------------------|-----------|---|---|-------------------------------|--|
| Jute | 242 | dry | 46 | 1.9 | 14.5 | 18.9 |
| | | wet | 41 | 2.1 | 10.3 | 17.1 |
| Glass | 600 | dry | 289 | 2.7 | 57.6 | 48.2 |
| | | wet | 283 | 2.9 | 57.8 | 47.2 |
| Jute multilayer fabric (MLG 1–warp) | 242 | dry | 50 | 3.6 | – | – |
| | | wet | 52 | 10.1 | – | – |
| Jute + Polypropylene multilayer fabric (MLG 4–warp) | 242/137 | dry | 47 | 2.3 | – | – |
| | | wet | 44 | 3.7 | – | – |

The flat knitting technique is the textile process most suitable for the geometrically adjusted 3D-reinforcement of wood components. Therefore, the applied reinforcing structures are mainly produced using this technique. By using flat knitting techniques, highly drapeable 2D-reinforcing structures as well as 2D- or 3D-reinforcing structures (outer contour and 3D-design) appropriate in form can be produced. The reinforcing impact is, on the one hand, achieved by integrated binding elements (loop, float) according to the load or, on the other hand, by reinforcing binding elements (e.g., glass filaments or natural fibre) integrated as weft and warp yarn. For the development of 3D-reinforcing structures, the multilayer flat knitting technique is combined with the fully fashion technique developed for upper knitwear processing and the intarsia technique.

The systematic development of suitable pre-forms also includes the development of reinforcing structures with respect to:

- the corresponding process-related shaping possibilities
- the influence of textile and machine parameters on the textile structure as well as
- the integration possibilities of natural fibres as well as high performance yarns (for an additional increase of the mechanic characteristics) such as warp or weft yarn systems or as loops or floats placed according to demand

The yarns were tested in a tensile test in a moist and a dry state to be able to make statements on the effect of the moisture necessary for the deformation process of the wood component and the stress decrease in the glue line. They were tested according to DIN EN ISO 13934-1 as strip tensile tests. The textile natural fibre yarn and surface formation were characterized in accordance with given test regulations, see Table 1.

The determined data clearly shows that the mechanic properties of the yarns experience oscillations between the dry and moist state. Only for the examined strain of jute multilayer fabric, they show differences. The reasons for this are to be found in the fibre structure and additional fabric strain.

The production of multilayer knitted fabric therefore offers a clear improvement of the productivity during the component production when the draping characteristics are adjusted for the entire structure. Furthermore, there is an excellent protection against delamination of the single layers of the multilayer knitted fabric in the composite component because of the stitch system connecting the single reinforcing layers. The fantastic drape characteristics of the multilayer fabrics result from the loop-related integration of the reinforcing fibres. This way, the fibre bundles in multilayer fabrics can, opposite to those in multiaxial ones, in which the fibres are broached in the stitch-forming process, slide onto each other and therefore illustrate superior geometries without wrinkles. Fabrics of the twill and sateen binding type achieve a medium position between multiaxial fabrics and multilayer fabrics with respect to drapability when compared to similar structures.

The research was intensified for the production of multiaxially reinforced surface formation after basic tests had not proven to be constructive concerning the reinforcement by unidirectional structures due to the multiaxial load of the reinforcing structure during the wood deformation. The commercially available and obtained natural fibre yarn only showed little suitability for further processing in textile surface forming processes due to their large yarn diameter or yarn counts. As a result of this analysis, three fabrics made of jute with different areal densities and areal masses (Fig. 3) were purchased.

On the basis of the preferred fabric, chosen because of the research carried out, a processing concept for the

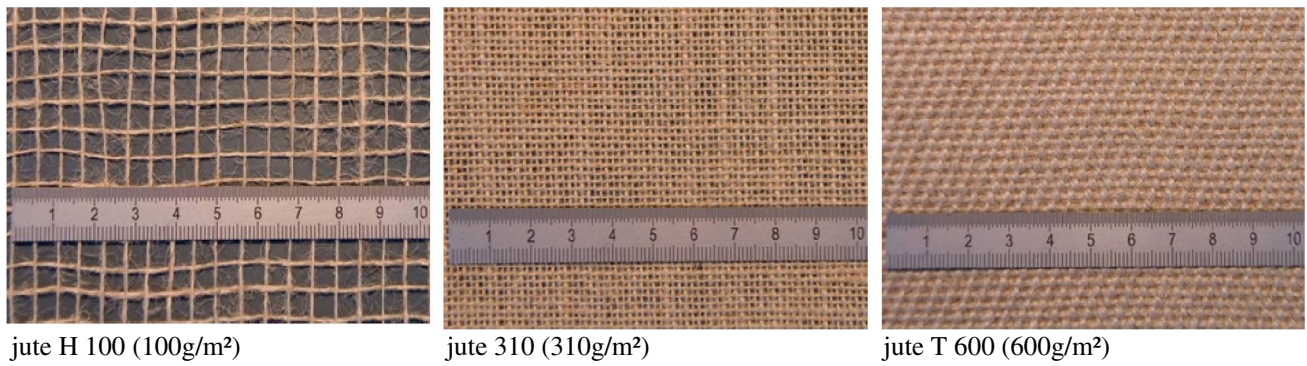


Fig. 3 Jute fibre structures for the reinforcement of end grain boards

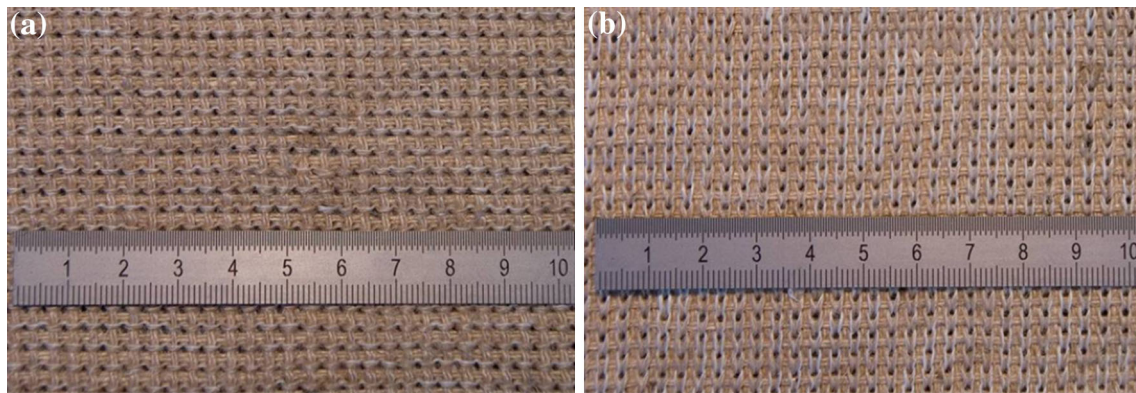


Fig. 4 Biaxially reinforced multilayer fabric made of jute fibres. **a** Left side of the fabric jute-MLG 4, **b** Right side of the fabric jute-MLG 4

realization of multilayer fabrics with similar structural parameters, using the flat knitting technique, was developed (Fig. 4). Here, it was important to consider another yarn system during the production of fabric in comparison to weaves. The machine system fixes the reinforcing fibres in warp and weft direction in a biaxial fabric. This is necessary for the linking and the dimensional stability of the textile structure, since in comparison to one fabric, there is no connection of the threads between warp and weft thread systems. The stitch system represents the biggest challenge for the production of multilayer fabrics. Due to the many changes in the direction at the working tools during the stitch-formation, the loop threads were mechanically loaded in a significant way. Furthermore, the high inhomogeneity of the yarn material as well as the previously mentioned hairiness problems reoccurred during the processing of the natural fibre in the stitch yarn system. The illustrations exemplarily show the different sides of a reinforcing textile processed using a flat knitting technique.

In Table 2, structural characteristics of the processed and commercially purchased structures are listed. The multilayer fabric (MLG 4) was produced by the methods described here and used for the reinforcement of end grain boards and components.

Table 2 Structural characteristics of the tested materials

| Sample | Name | Weft yarn density (SF/dm) | Warp yarn density (KF/dm) | Stitch length (mm) |
|-----------------------------|----------|---------------------------|---------------------------|--------------------|
| Fabric jute H 100 | fabric 1 | 15.4 | 18.2 | – |
| Fabric jute 310 | fabric 2 | 55.9 | 66.8 | – |
| Fabric jute T 600 | fabric 3 | 51.1 | 47.9 | – |
| Fabric jute | MLG 1 | 29.3 | 28.6 | 13.4 |
| Fabric jute + Polypropylene | MLG 4 | 28.9 | 28.3 | 14.5 |
| Fabric glass | MLG 5 | 29.2 | 28.5 | 12.3 |

2.3 Operating principles and processes of composite elements and modification analysis

The manufacture of sandwich structures based on end grain boards took place with different textile structures (see Table 2). The reinforcement was applied on one side using 1-component polyurethane. The glue line on the end grain board to control the strain area was designed in three different patterns: (a) complete, (b) grid of 40 by 40 mm² and (c) circumferential line. To prevent deeper infiltration, the wood surface was wiped with a wet cloth. Further, the

Table 3 Process steps and influential parameters during forming according to Heisel and Otto (1994)

| plasticisation | → | densification | → | forming | → | fixation |
|--|---|---|---|---|---|--|
| <ul style="list-style-type: none"> • moisture • temperature • pressure • methods • time | | <ul style="list-style-type: none"> • moisture • temperature • pressure • methods • speed • densification degree | | <ul style="list-style-type: none"> • moisture • temperature • compressive force • methods • component geometry • bending radius | | <ul style="list-style-type: none"> • moisture • temperature • methods • time |

textile structures were glued and pressed for stress distribution by using a layer of foam and release paper. The pressing time was 24 h.

In order to optimize the deformation potential, it was necessary to analyze the compression process. For this, three different types of wood (*Pinus silvestris* L., *Populus hybrid* and *Tilia cordata* Mill.) were modified under different conditions and analyzed with respect to the usable strain. Apart from the directly controllable process parameters (Table 3), limitedly influenceable material parameters (wood, textile, glue characteristics) had to be taken into consideration. Moisture, temperature and compression degree as significant influential factors were regarded closely in several tests.

The wood samples ($60 \times 60 \times 50 \text{ mm}^3$) were cut into 10 mm thick end grain pieces after biaxial compression and stored in a 25 °C water quench. Thereafter, their recovery was analysed under photogrammetric and time aspects. The storage in a water quench lasted 1 h, and five to six samples were tested at once (Wehsener 2008).

The characterization of the deformation behaviour was carried out on the basis of the GSA method “Grid Strain Analysis” (GSA). It forms the mathematical relation between a line of marks on the sample surface before and after the deformation in order to determine the strain. Together with other strength values, it serves for the creation of a forming limit diagram (FLD) to determine the changing curve limit form.

All wood samples were ground on both sides of the end grain surface with a grain size of 120 and marked with a grid pattern. The stamped line grid on the wood surface was $5 \times 5 \text{ mm}^2$. Besides the simple and reproducible application to the wood surface, covering of macroscopic structure elements (growth ring, fiber irregularities, pores) is avoided. Evaluation of the different marks was done using an optical measurement system with automatic marks of the crossover points in X- and Y-direction by specially developed software. Recording of the form changes was done by measurement of the grid net lines before, during and after the form changes of the wood. At this, the marks are measured and the strains in the main and sub directions were calculated. Evaluation of the displacements was noted

down in a table and a graphic illustration. The illustration of the percentage deformation or the standard deviations of the percentage deformation provides information about the homogenization of the density.

3 Results and discussion

3.1 Density measurement

The density correlates with different strength characteristics of wood. It is an important indicator for the determination of the pore percentage and the void distribution. With increasing densification the density and swelling pressure also increase. Stresses and strains occurring in densified end grain boards have to be compensated by textile reinforcement. At the same time, the acquisition of a density profile provides conclusions regarding the deformations (potential strain). The measurements were recorded before, during and after the individual process steps on a gamma-ray basis (gamma source Am^{241} , Raytest Isotopenmessgerät GmbH). The measurement precision was 1 % when the g-rays were recorded per 0.1 mm. The density changes were tested vertical and horizontal to the densification direction. With increasing deformation, the density of the wood samples increases. Since the g-rays have a measurement area of about 5 mm, mixed values were created by diffuse test body geometries and density limits (early and late wood).

A homogenous densification could be measured across all the growth rings in the early wood during uniaxial radial compression. With increasing densification, a proportional increase in density was recorded. The densification perpendicular to the annual rings caused buckling and irregular density distribution. They appear as a local maximum in the density profile. It caused maybe inhomogeneity to later forming. A similar behaviour of lime and poplar and stronger than that of pine can be observed.

The recording of the density profile at biaxially densified test bodies was carried out in radial and tangential direction before and after the deformation (Fig. 5). The density rose twice from 500 kg/m^3 with a steep rise between late and

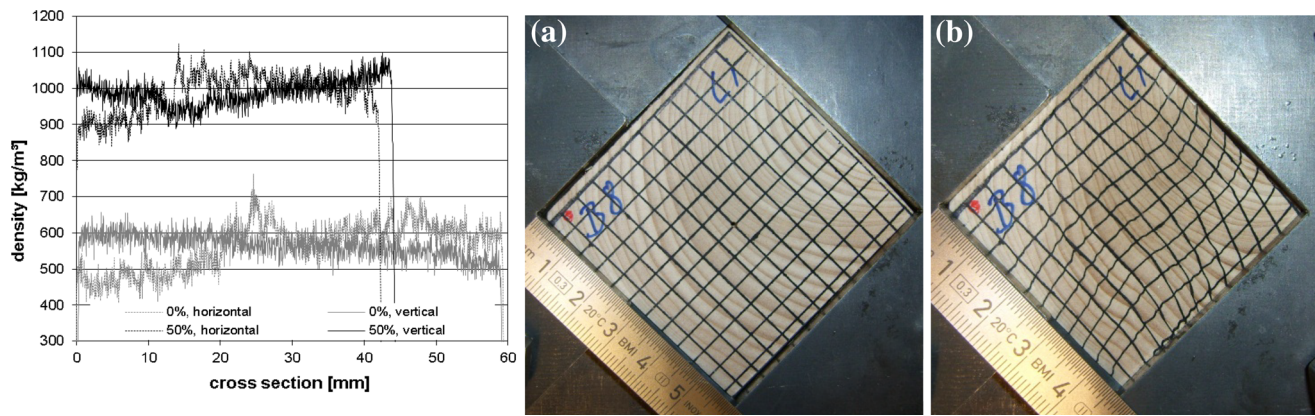


Fig. 5 Density profiles of radially (*horizontal*) and tangentially (*vertical*) uncompressed (a) and 50 % compressed (b) lime

Table 4 Swelling pressure of different wood types and degrees of densification

| Densification degree (%) | Density (kg/m ³) | | | Swelling pressure (N/mm ²) | | |
|--------------------------|------------------------------|------|--------|--|------|--------|
| | Pine | Lime | Poplar | Pine | Lime | Poplar |
| 0 | 427 | 572 | 341 | 0.94 | 0.98 | 0.33 |
| 25 | 533 | 634 | 418 | 1.26 | 1.31 | 0.53 |
| 33 | 567 | 781 | 456 | 1.23 | 1.56 | 0.44 |
| 42 | 606 | 803 | 478 | 2.19 | 1.58 | 0.48 |
| 50 | 640 | 946 | 511 | 2.43 | 2.64 | 0.47 |

early wood. They showed a less homogenous behaviour with a global increase in density (Table 4). With increasing deformation buckle, the late wood cells penetrate into the low density areas. The distribution of deformation was inhomogeneous. A local density increase was recorded in the deformation analysis.

3.2 Swelling pressure test

The research was carried out with reference to Perkitny (1958) (see Fig. 6), using water storage (25 °C) with a pre-tension of 0.01 N/mm². The sample dimensions were 50 × 60 × 60 mm³ (L × W × H) with different densifications (Table 4). The measurement was carried out in a universal force pressure testing machine for a maximum of 240 h or until the maximum tension was exceeded.

The measurement of the swelling pressure of densified wood is necessary for the estimation of the inner tension at the glue joint and for the alignment of the textile reinforcement. The tension strength per roving of 41N and 283N was used as the basis for textile reinforcement of wet jute and glass fibre. The strain was 10 % for jute and 3 % for the glass fibre structure (Table 1). When a limit value of swelling pressure is exceeded, the glue line or textile reinforcement fails.

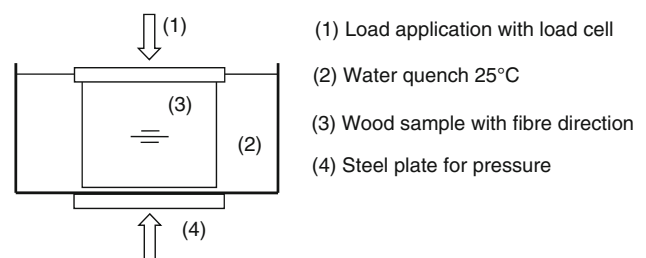


Fig. 6 Schematic test set-up with test bodies in water quench

Perkitny (1958) and Keylwerth (1962a, b) determined similar values for the tangential and radial swelling pressure of non-compressed pine wood in dependence of the conditions (see Table 4). Unevenly compressed woods lead to inhomogeneous densifications during the recovery. Normal tensions are created at uniaxially densified end grain boards during deformation. The strength of the glue joint is only limitedly influenced by large recoveries vertical to the fiber direction in contrast to biaxially densified end grain boards. Due to the compression and the biaxially running glue line, large tensions are caused on the deformations. The swelling pressure tensions are transferred onto the adjacent wood by a wood segment through the glue and are then decreased. A supporting effect during the reduction of the tension is hereby caused by the textile structures.

The amount of swelling pressure is dependent on the pre-tensions and the degree of densification for similar wood samples. With increasing density, the relative amount of swelling pressure tensions increases as well. The maximum swelling pressure of lime at 50 % densification is reached after 200 h. The stress- and strain limitation of forming is given by the textile structure. The textile reinforcement must be dimensioned according to the requirements of bending radius, thickness, wood species and density.

Densified end grain boards have high strain in the plate area and low strength vertical to it. During the formation

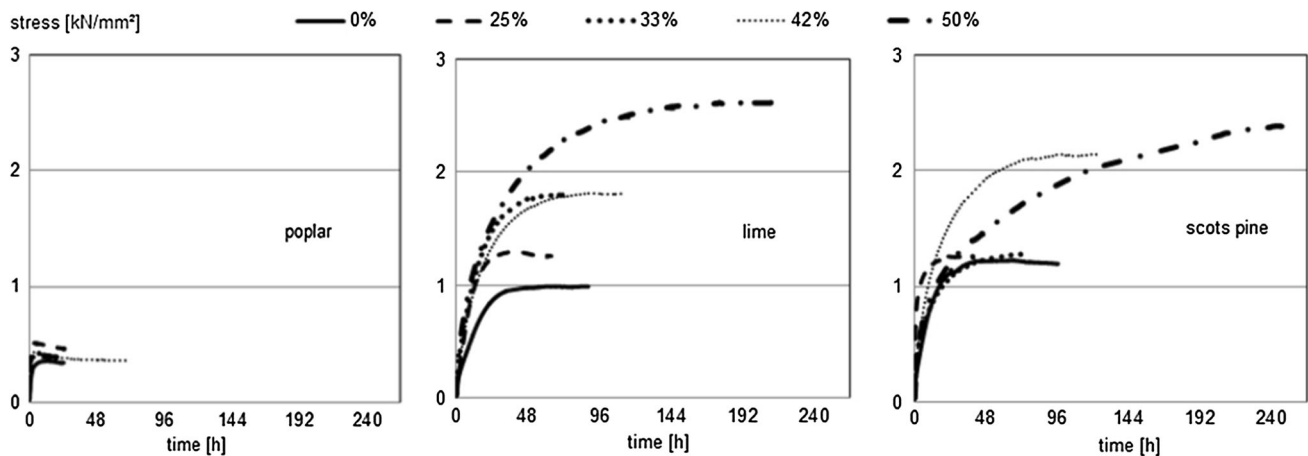


Fig. 7 Swelling pressure of poplar (*Populus nigra* L.), lime (*Tilia cordata* Mill.) and pine (*Pinus silvestris* L.)

process at high wood moisture (18 %) and temperature (90 °C), the strength in the glue joint is reduced, while at the same time the swelling pressure and the bending tension are increased. Uneven compaction leads to tension concentrations by wedged swelling.

As a result of the tests, an increase in the swelling pressure was recorded with increasing density and densification degree (Fig. 7). The values for poplar are about one-third of those of lime, with a density which is about one-third lower. In contrast to the raw density values of pine wood, the swelling pressure tensions of lime achieve similar values despite a 25 % lower density. Furthermore, the increase in tension is less steep in native hardwood than in softwood. The swelling pressure in non-compressed pine reached the maximum a lot faster than that in densified samples. The maximum value in densified and undensified poplar has already been achieved after a few minutes below 0.5 N/mm². The increase in the swelling pressure in 50 % densified pine was slower than that of undensified pine. Possible reasons can be found in the bonding of the cell walls by resin and in the small cell lumen.

The tensile strength of textile reinforcement on densified wood can compensate the appearing swelling pressure. When using this highly densified wood, an enhancement of the reinforcement ratio is necessary. In general, the degree of densification will be lower than 50 %.

3.3 Deformation analysis

The GSA (Fig. 8a, b) was used for unreinforced end grain cross sections to optimize the modification parameter, determine the strain and calculate the textile reinforcement in direction and strength. Local material inhomogeneities can be compensated. In Fig. 8c, deformations with isolines are presented using the example of a pine wood sample. Essential differences are shown between the deformation

of hardwood and softwood. While the biaxial densification is even for hardwood due to the homogenous anatomic structure in contrast to softwood, the influence of the high moisture is also positive for the evenly distributed deformation. The densification at high speed leads to high deformations for all wood samples in the border area. When wood samples were compressed at 125 °C, this short thermal treatment led to already delayed water absorption due to hornification and bonding of the cell walls with negative impacts on the recoverability speed. A comparison of the effects of the different influential parameters on the forming characteristics of solid wood leads to the result that at biaxial densification, optimal strain reserves can be adjusted at high moisture, high temperatures and low compression speeds. The type of wood, the position of the growth rings, the density and the densification degree all influence the distribution of the deformations in the middle and variance for the realization of usable deformation potentials. Hereby, the basis is a homogenous distribution of equal deformations for the moulding in XY-direction. All in all, the variance was taken as the rule for the evaluation of the formability for an optimum deformability.

The realization of homogeneously distributed strain reserves with low deviations is presented in Fig. 9 using pine wood as an example. They show that the increase in wood moisture from 8 to 18 % under constant conditions has a low impact on the homogenous densification. In contrast to that, a temperature of 125 °C has a lower oscillation under differently high densifications and wood moisture. Furthermore, increasing densification by more than 30 % can be expected with higher deviations with the applied deformations, which, however, comes close to a maximum value above a compression of 30 %. Densifications above 50 % complicate the recovery of wood. In general, pressure deformations for the insertion of stress reserves with higher temperatures and lower moisture, with

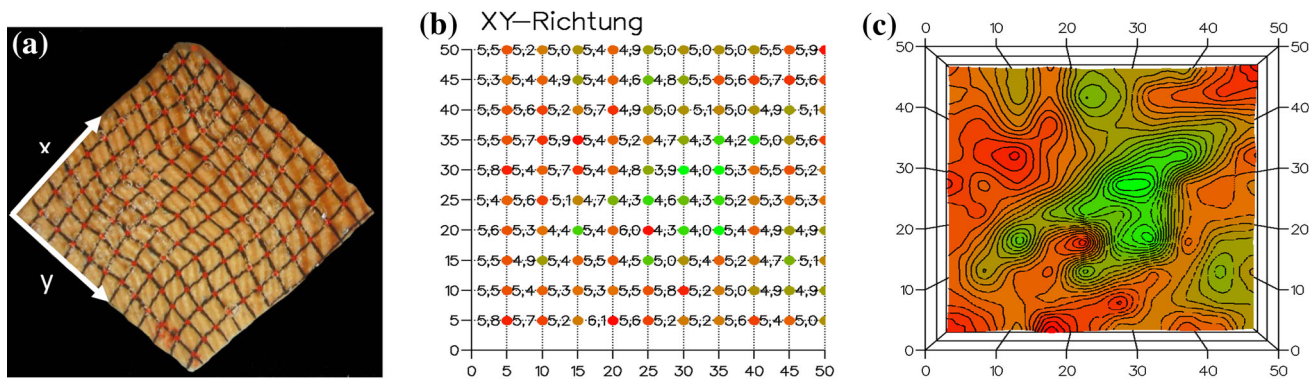


Fig. 8 Illustration of the displacement of the wood sample (pine) as number matrix and as isolines

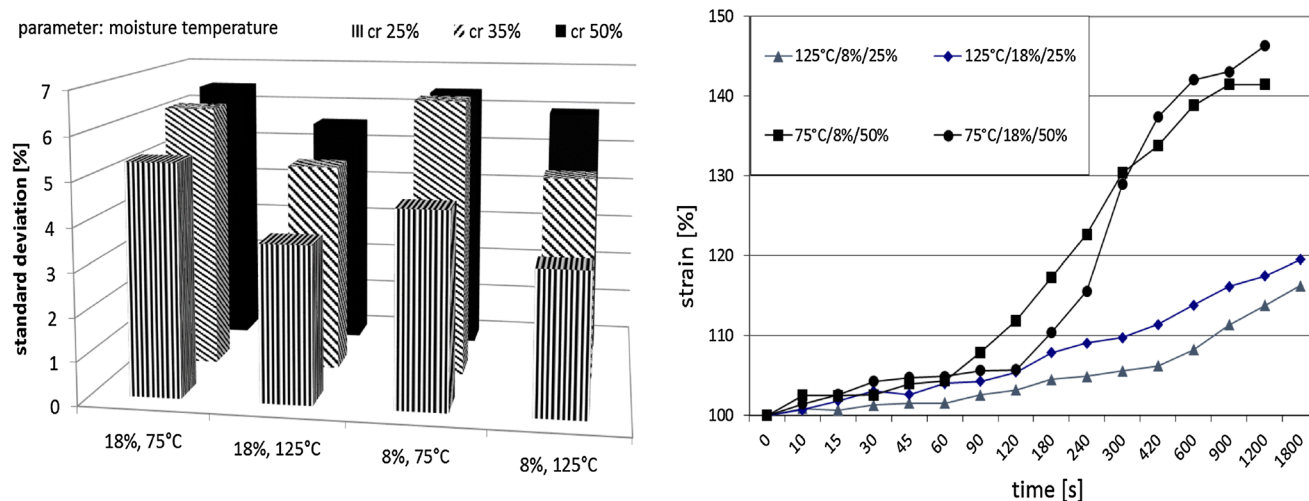


Fig. 9 Influence of moisture and temperature on the deformation with respect to standard deviations and recovery speed

respect to the target function of the necessary strain, are carried out. The multiaxial moulding of end grain boards is basically determined by a homogenous densification profile. For the application of inserted deformations as strain reserves, however, its activation with different densification parameters (Fig. 9) is crucial. Besides the amount of recovery, the quality of the densification can be classified by the speed of the volume increase. It is done better for densified wood with lower temperatures and higher densification than with high temperatures. A fast and even recovery is another necessary prerequisite for good formability of the boards. In Fig. 9, the wood samples are exemplarily illustrated with different densifications with respect to temperature (75, 125 °C), moisture (8, 18 %) and densification ratio (25, 50 %).

3.4 Drape test

For analysis of the deformability of two-dimensional material, drape, burst and cupping tests were carried out in

different areas according to Erichsen on the basis of DIN ISO 20482. Based on the multiaxial deformation, probes of a small format (100 × 100 mm²) were placed on a template during the research on different materials (textile, metal, synthetic material). In the template, there is a spherical drill hole with a diameter variable depending on the analysed sample thickness. A stamp with a hemispherical cross-section was pressed into the mould as a test. The degree of deformability is the path of the stamp or the pressure force when the sample fails.

The general specialty of end grain plates is characterized by an anatomical position of wood. The fibre direction is vertical to the plate surface. It causes relatively even strength characteristics in the plate plane with a high pressure strength vertical to it. Decisive for the deformation of end grain plates is the diagonal tensile strength of the modified woods under a high stress in the plate plane on the one hand. On the other hand, the fibre orientation of the relatively thick samples prevents early buckling due to the surplus stock at the edge (Fig. 10).

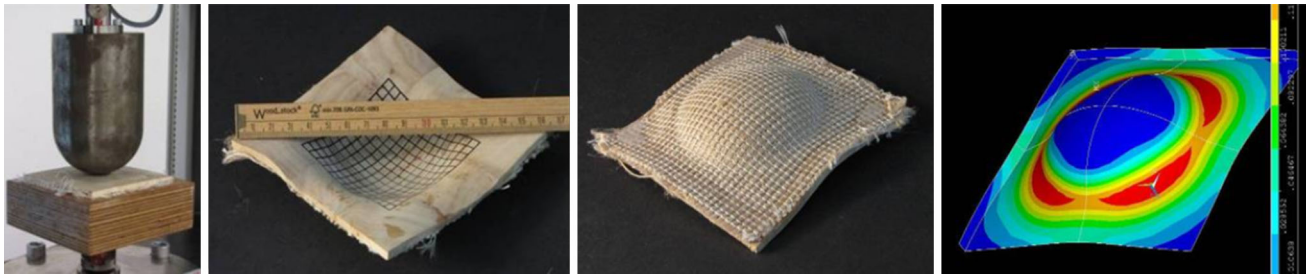


Fig. 10 Test set-up with marked and textile reinforced poplar end grain plate and stress calculation via FEM

End grain plates made of lime wood, poplar, beech and pine wood with and without textile structures were produced for the drape tests. The plate dimensions were $120 \times 120 \times 5 \text{ mm}^3$. The coating was done on one side with glass fibre and jute structure at a weight of 600 g/m^2 each. The bonding of the textile structure was applied outside the deformation zone with PUR-glue I12NV in a thick seam. The plates were stored in a water quench ($80 \text{ }^\circ\text{C}$) for 60 s prior to the plasticisation test. Before that, all plates were stamped on the unreinforced side with a $5 \times 5 \text{ mm}^2$ grid. Subsequently, the press test was done between stamp and template with a maximum of 19 mm stamp path. The radius of the stamp was 50 mm. The counterpart was processed with a 55 mm drill hole and 24 mm depth made of synthetic resin compressed wood.

The test results are presented in Table 5. They prove a high formability of poplar and lime wood. All unreinforced wood samples failed before the test ended. A failure of the glue joint or the wood structure could be seen when pine wood and beech end grain was deformed. The coating of textile structures (with adjusted stress of 3–8 %) led to high strainability when jute was used as much as when glass fibre was used with an extremely low stress for the improvement of the achievable deformability of the wood structures. Here, the textile reinforcements act as tensile strings. They compensate the low tensile strengths perpendicular to the grain of the wood (up to 5 N/mm^2) and displace the neutral line (balance between tensile and pressure tensions) in the direction of the convex test side.

The stress necessary for the illustration of the desired complex geometry of 12 % is lowered to about 8 %. The necessary stamp force and path were recorded during the test. The stressability adjusted in the wood structure has a significant influence on the achievable complexity of the component geometry during the shaping process. The textile reinforcement structures applied to the wood surface made of jute or glass fibre limit the stresses occurring during the formation of the wood plates and, therefore, prevent breaking inside the glue joint or in the wood structure. The even stress diagonal to the wood fibre in X- and Y-direction allows a high deformation from the plate plane in all tests. Due to the high deformations and the circularly occurring tensions around the press stamp, wrinkle formations occur in the corners of the test samples. They can be eliminated with the help of hold-down devices, which prevent drawing-in of the material. The exceeding of the maximum tensile strengths on the bottom of the press stamp causes cracks in the middle of the test sample. Evaluation of the grid pattern shows a relation of 30–70 % between the tensile and the pressure deformations. The tolerable strain of the jute structure is 8 %, while the maximum strain of the glass fibre structure is about 1 %. In good compliances from an FEM calculation, strain of up to 15 % occurs in unreinforced wood.

Evaluation of the drape tests shows high performance of poplar and lime wood with jute reinforcement. The maximum deformation of 19 mm was achieved without breaks or cracks in the glue joints. Unreinforced end grain plates

Table 5 Drape test for different wood species and textile structures

| Test sample | Compression load (N) | Standard deviation (N) | Displacement (mm) | Failure |
|-------------------------|----------------------|------------------------|-------------------|-----------------|
| Beech | 6,664 | 320 | 2 | Wood/glue line |
| Pine | 2,047 | 54 | 3 | Wood tangential |
| Lime | 1,120 | 23 | 17 | Wood radial |
| Lime glass reinforced | 3,470 | 67 | 19 | – |
| Lime jute reinforced | 3,911 | 149 | 19 | – |
| Poplar | 891 | 23 | 10 | Wood tangential |
| Poplar glass reinforced | 2,645 | 40 | 19 | – |
| Poplar jute reinforced | 2,989 | 62 | 19 | – |

made of beech failed due to breaks of the glue joints at a 3.8 mm press path, while the pine wood failed on average after 8 mm due to wood breakages. Poplar and lime tree fail between 80 and 90 % of the maximum deformation path. It is characterized by a homogenous deformation picture due to a low density difference within the growth rings and homogeneously distributed densification. The necessary press power is the highest for beech and pine wood due to the higher modulus of elasticity. Fibre-reinforced test samples of poplar and lime wood need about three times as much pressing force as unreinforced referential test bodies.

4 Application fields for 3D-moulded woods

The production of triaxially deformed solid wood is carried out on different shapes with different bending radii. As a result of the pre-tests on end grain plates with and without textile structures, a complex mould shape in aluminium is developed for the illustration of shaping possibilities. The production of wood plates is carried out industrially with reproducible characteristics in the wood species poplar, lime and pine. After the occurring strains were determined (Table 6) by disassembling in main and sub direction, modified plates with textile structures were coated. For example, the forming of the platter (Fig. 11) was determined by stretching and compressing of end grain boards in two directions: radial and tangential. The bending radius in radial and tangential direction was 20 mm minimum. The influenced forming area of end grain boards on each radius (RI to RIV as “Bending length”) was also calculated. The base line defined the stress-free line inside the board in relationship to the ratio of tension and compression stress (RI/RIII and RII/RIV).

The deformation took place by pressure and tensile deformation after pre-treatment in a water quench at 80 °C. The maximum strain was determined on the bottom of the hull in radius RIII with just under 18 %. By applying a textile jute structure, the tolerable strain in the wood is restricted to 10 % and is compensated by an increased compressive strain in the pressure area. Afterwards, the shaped plates were fixed, dried and the surfaces finished.

For the application of textile structures on the wood surface, different fixation patterns were analyzed. The reinforcing structures were fixed on the wood samples two-dimensionally, in a grid structure and rotary in lines.

The best results could be achieved by the rotary fixation (Fig. 11), since no negative impacts occurred in the deformations taking place in the formation zone.

For the illustration of a high formability, more wood shapes (Fig. 12) were developed and realized besides the hull. For this, up-scaling to larger dimensions became necessary. In the “fender” shape, two different bending radii in longitudinal and lateral direction of $r_L = 300$ mm and $r_Q = 100$ mm were realized on a plate size of 800 mm × 400 mm. The plate thickness was 10 mm. The “wave” model was realized with textile reinforcement made of jute to a 1,100 mm × 1,100 mm and 20 mm plate thickness. The bending shapes were realized using synthetic resin compressed wood. All 3D-wood parts with and without textile reinforcement structure only need low pressure forces due to the easy deformability after the plasticisation and are reproducible with a hand press. Coating was carried out with an adjusted coating system and leads to safe fixation of the formed plate elements. Especially by integrating functional and reinforcing elements, numerous application possibilities in architecture and interior fitting result.

Table 6 Maximum strains in the corners of the hull

| | Radius I | Radius II | Radius III | Radius IV | Cross section of platter |
|-------------------------------------|----------|-----------|------------|-----------|--------------------------|
| Measure (mm) | 20 | 30 | 25 | 25 | |
| Bending length (mm) (marked with R) | 15.71 | 23.56 | 19.63 | 19.63 | |
| Base line length (mm) | RI/RIII | | RII/RIV | | |
| | 16.89 | | 20,81 | | |
| Strain (%) | | | | | |
| Tangential | 6.98 | -13.21 | -16.28 | 5.66 | |
| Radial | 7.69 | 2.70 | -17.95 | -6.31 | |



Fig. 11 Bottom part of the mould (*left*), end grain plate made of cottonwood with textile structures (*middle*) and illustration of FE-shaping with occurring shear stress (*right*)



Fig. 12 Examples of moulded end grain boards of $900 \times 800 \times 20 \text{ mm}^3$ “wave” and $500 \times 250 \times 10 \text{ mm}^3$ “fender” made of lime

5 Conclusion and outlook

The thermo-mechanic compression realizes stress reserves in the wood structure which can be used for the non-chipping forming with a special method using a tensile stress deformation according to DIN 8580. The structure of the wood and its plastic formability under warmth and moisture allow for a new material understanding, which realizes wood as a cellular solid body. By applying textile reinforcing structures according to demand, the formability as well as the bearing capacity can be increased once the forming process is completed. With respect to the reinforcing textiles designed according to demand on the basis of natural fibres, material composites made of renewable resources evolve.

A variation of this process consists of producing thin panels from square, biaxially compressed segments with a fibre direction oriented perpendicular to the fibre of the end grain board. This approach allows the manufacturing of 3D shells with a strong double curvature (Fig. 12). The semi-finished products have to be moulded after calculation of the expected stress. The example of textile reinforced end grain platter showed the capabilities of this

technology. The process used strain of a textile jute structure of 10 %, glued together with densified wood. The compressed material could be recovered in warm water or under a saturated steam atmosphere. The moulding behavior is influenced by the densification process. It was shown that swelling pressure increases with higher densification ratio. The recovery speed and the homogeneity are also influenced by the densification process. Applied textile structures are used in order to enhance the moulding ability.

Depending on the degree of densification, the recovering potential is theoretically higher than 50 %. In a pre-industrial process, the moulding technology was tested. After moulding and fixation, the surface was coated with protective layer.

Deformed end grain plates are characterized by special strength and fracture characteristics as well as distinct visual appearance, surface feel, and acoustics.

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