Shear coupling effects on stress and strain distributions in
wood subjected to transverse compression

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Abstract

The mechanical behaviour of a wood board subjected to transverse compression is relevant to the performance of glulam beams and solid wood structures. The wood material can be described as polar orthotropic, due to the annual ring structure and to the differences in moduli in different directions in the radial–tangential plane. Strain measurements are performed on single wood boards using a whole-field digital speckle photography technique. Finite element analysis is performed and compared with experimental data. Good agreement in terms of strain fields and apparent moduli is observed between predictions and data. The experimental data show strong variations in local strain due to the polar orthotropic behaviour of wood in this plane, and the extremely low value for shear modulus \( G_{rt} \) as compared with the other moduli. This leads to shear coupling effects resulting in large local shear deformation and correspondingly low effective stiffness under transverse global loading.

Keywords: A. Wood; B. Transverse stiffness; B. Polar orthotropy; B. Shear coupling; D. Digital speckle photography

1. Introduction

Wood is a true composite material with orthotropic properties. Although analysis based on composite mechanics is not commonly used in product development, the approach is a necessary ingredient in design procedures for new and more efficient wood products. In analogy with aircraft structures, stress analysis in combination with experimental mechanics will contribute to improved understanding of structural performance, better design procedures and also lead to improved structures and materials. The principal material axes of orthotropy in wood are defined by the longitudinal \( l \)-axis parallel to the grain and by two axes perpendicular to grain, the radial \( r \)-axis (normal to annual rings) and the tangential \( t \)-axis (in the tangential direction of annual rings). The elastic properties and strength of wood in the \( r–t \)-plane are at least one order of magnitude lower than along the \( l \)-axis. In addition, the radial modulus \( E_r \) is typically twice as high as the tangential modulus \( E_t \). The shear modulus \( G_{rt} \) is very low, about 1/20 of \( E_r \), in the softwoods commonly used in load-bearing applications.

For structural analysis, the importance of wood properties along the grain is recognized, whereas the properties across the grain are often neglected. Thus, a recent text states that elastic properties in the \( r–t \)-plane can be considered isotropic and equal to the tangential stiffness \( E_t \), while still providing sufficiently accurate results in stiffness analysis of wood structures [1]. This is a gross simplification, as will be apparent from the present study.

Early phenomenological studies of wood orthotropy in the \( r–t \)-plane showed a strong dependency of elastic properties on the orientation of annual rings to the loading direction (e.g. [2,3]). In the latter study, it was also found that the apparent stiffness of wood under “off-axis” loading (the annual rings are neither parallel nor orthogonal to the loading direction) was significantly lower than \( E_r \) and \( E_t \).
Although not discussed explicitly in these studies, this finding indicates that the off-axis response is strongly influenced by shear deformations due to the low $G_{rr}$. Wood orthotropy is additionally complicated by the circular annual ring pattern and resulting cylindrical or polar symmetry in the $r$–$t$-plane. As a consequence, a complex and inhomogeneous stress state may exist in wood boards, despite simple uniaxial loading. Recently, Hoffmeyer et al. [4] presented results of finite element (FE) analysis of structural timber and glulam beams in transverse compression. Accounting for polar orthotropy, their results demonstrated very inhomogeneous and complex stress fields along the loading direction of transversely compressed glulam beams. The stress distribution perpendicular to the loading direction was also complex, including compressive stresses in some regions and tensile stresses in other regions.

The complexity of stress and strain fields in glulam cross-sections (composed of many boards, or rather plies) subjected to transverse compression, suggests a need for basic studies on the simpler case of a single board. Although the board was oriented 90° to the transverse glulam case, Aicher et al. [5] indeed investigated the effect of polar orthotropy in the $r$–$t$-plane of a single board. An attempt to measure strain distribution was also undertaken by the use of strain gauges bonded to the test specimens. Good agreement was observed between FE predictions and experimental results. However, the strain gauges only allow for discrete strain measurements at the locations where they are present. The consequences of cylindrical orthotropy on strain distribution are rather non-intuitive, as will be apparent in the present study. Neither the locations of strain concentrations, nor the criteria for positioning of strain gauges are obvious.

In the present study, we determine the complete strain field in a wood board loaded transversely, in the direction relevant to the glulam case. The objective is to gain enhanced physical insight into the nature of strain fields, the significance of shear coupling and polar orthotropy. FE analysis is applied in order to compare with experimental strain data and to determine stress distributions. The strain field data are sampled by the full-field, digital speckle photography technique (DSP). In a longer term perspective, results are helpful in the analysis of transverse performance of glulam beams. As an example, adhesive bonds in glulam beams are subjected to very complex stress and strain states due to the strong shear coupling effects in the wood boards. Improved performance of the adhesive bonds is therefore not only a question of properties of the bond line, but also of the choice of annual ring pattern in the boards.

2. Polar wood orthotropy

Wood properties are typically defined in a cylindrical (or polar) material coordinate system $(r, t)$ with the origin in the centre commonly denoted “pith”. Wood boards could be sawn from the log in different ways and the geometry of the board cross-section is defined in a Cartesian coordinate system $(x, y)$. The location of material coordinate system $(r, t)$ with respect to the geometrical coordinate system $(x, y)$ defines a so-called sawing pattern in a wood board. Thus, the material in wood boards sawn near the pith is characterised by polar orthotropy attributed to the distinct annual ring curvature, as illustrated in Fig. 1(a). Close to rhombic orthotropy can be obtained in boards cut from the peripheral part of a log so that the annual rings are almost straight (Fig. 1(b)).

In stiffness analysis of structures, it is often unnecessary to consider the porous, heterogeneous nature of wood and account for localised stresses and strains in the individual annual rings. In this case, the wood structure is usually homogenized and represented as a continuum with effective properties. Assuming plane stress, wood is then characterised by four independent elastic constants $E_r$, $E_t$, $G_{rt}$ and $v_{rt}$ in the $r$–$t$-plane. Homogenization is also advantageous since the effective properties are assumed to be the same irrespective of how small the material volume is. This enables application of classical elasticity theory for establishing the relationships between stresses and strains.

Orthotropy with rhombic material symmetry is well established and widely used for man-made composites (see [6]). It can also be applied to a wood board with rhombic orthotropy (Fig. 1(b)). For example, under plane stress condition the apparent elastic stiffness modulus $E_y$ for the board with rhombic symmetry can be expressed as

$$\frac{1}{E_y} = \frac{\sin^2 \theta}{E_r} + \frac{\cos^2 \theta}{E_t} + \cos^2 \theta \sin^2 \theta \left( \frac{1}{G_{rt}} - \frac{2v_{rt}}{E_t} \right)$$

(1)

As can be seen from Eq. (1), $E_y$ depends only on elastic constants and the angle $\theta$, which defines the rotation angle between geometrical coordinate system $(x, y)$ and the principal material $(r, t)$ axes. It is obvious that the orientation of material principle axes is fixed and therefore, the angle $\theta$ is also constant for the whole cross-section of the board.

Fig. 1. Wood board with (a) polar orthotropy and (b) rhombic orthotropy.
with rhombic symmetry. Assuming that the board is subject to a uniform uniaxial stress field \( \sigma_y = 1 \) MPa, the strain \( \varepsilon_y \) is

\[
\varepsilon_y = \frac{1}{E_y}
\]

(2)

In contrast, in the board with polar orthotropy the orientation of material axes with respect to the geometrical coordinate system \((x, y)\) can be assumed fixed only for an infinitesimal element, see Fig. 1(a). Thus, the angle \( \theta \) is not globally fixed but depends on the geometrical location of an infinitesimal element in the board, so that \( \theta = \theta(x, y) \). Therefore, computation of apparent global engineering constants is not so simple as for the rhombic orthotropy case in Eq. (1). However, for the infinitesimal element with coordinates \((x, y)\) the “local” apparent engineering constant \( E_{y}(x, y) \) can be defined as

\[
\frac{1}{E_y(x, y)} = \frac{\sin^4 \theta(x, y)}{E_r} + \frac{\cos^4 \theta(x, y)}{E_t} + \cos^2 \theta(x, y)
\]

\[
\times \sin^2 \theta(x, y) \left( \frac{1}{G_{rt}} - \frac{2v_{tr}}{E_t} \right)
\]

(3)

In analogy with Eq. (2), the strain \( \varepsilon_y(x, y) \) for the infinitesimal element of the polar symmetry board subjected to a uniform uniaxial stress field \( \sigma_y = 1 \) MPa can be derived as

\[
\varepsilon_y(x, y) = \frac{\sin^4 \theta(x, y)}{E_r} + \frac{\cos^4 \theta(x, y)}{E_t} + \cos^2 \theta(x, y)
\]

\[
\times \sin^2 \theta(x, y) \left( \frac{1}{G_{rt}} - \frac{2v_{tr}}{E_t} \right)
\]

(4)

Obviously, both the local apparent engineering constant \( E_y(x, y) \) and the local strains \( \varepsilon_y(x, y) \) alternate with the geometrical location of the element within the board. It can be shown that the apparent stiffness \( E_y(x, y) \) is high in the areas located at the angles \( \theta = 0 \) and \( \theta = \pi/2 \) where the magnitude of \( E_y(x, y) \) is only governed by the tangential and radial stiffness \( E_r \) and \( E_t \), respectively. For angles \( 0 < \theta < \pi/2 \), the apparent stiffness of the board \( E_y(x, y) \) (Eq. (3)) is a function of all four elastic constants \( E_r, E_t, G_{rt} \), and \( v_{tr} \). Recalling that the shear modulus \( G_{rt} \) is as low as about 1/20 of \( E_r \), it can be shown that for wide interval of angle \( \theta \) in Eq. (3), the term containing \( 1/G_{rt} \) is dominant. Therefore, the apparent stiffness of a board with polar orthotropy is governed by the small shear modulus value \( G_{rt} \). This leads to a pronounced shear coupling effect on board stiffness in the off-axis loaded regions of the board. A qualitative illustration of the complex strain distribution in the board with polar orthotropy can be obtained by dividing the board into thin strips and numerically solving the analytical expressions Eqs. (3) and (4) [5]. Even though such an approach is a rough approximation which does not meet the basic criteria for application of elasticity theory, it demonstrates the effect of polar orthotropy in wood. A more accurate analytical solution would require application of force equilibrium and boundary condition equations, in order to solve for displacements and stresses by Fourier integral transform. Such an analytical solution would be very complicated whereas a more simple and accurate solution can be obtained by the FE analysis, as done in the present study.

3. Experimental study

The aim of experimental study is to determine the effect of polar orthotropy on the strain distribution in wood. Also, the applicability of the digital speckle photography technique for full-field strain measurements in wood is of interest. Therefore, experimental data from only two specimens are presented although several tests were conducted yielding similar results. The chosen boards show the best symmetry in terms of annual ring structure in the board.

3.1. Specimens and test procedure

For the experimental study, a board of European Spruce was sawn from the central part of a log with a longer side of the cross-section parallel to the radial direction as shown in Fig. 2. The pith was located in the centre of the board and the cross-sectional dimensions were \( L = 160 \) mm and \( b = 30 \) mm. Two prismatic specimens were cut from the same cross-section, as presented in Fig. 2. The “centre” specimen was sawn close to the pith where the annual ring structure is characterised by a distinct curvature. The “periphery” specimen was cut from the outermost location in the board, at the distance \( r = 60 \) mm from the pith to the top edge. The annual ring curvature was negligible. The dimensions of the specimens in the \( r-t \)-plane were \( b = 30 \) and \( h = 20 \) mm. The thickness in the \( l \)-direction was 15 mm. The average annual ring thickness was about 2 mm for the “periphery” specimen and 3.3 mm for the “centre” specimen.

![Fig. 2. Geometry and location of test specimens in the board.](image-url)
The specimens were conditioned at 55% RH and 23 °C for several months. Testing was conducted at the same conditions. Using the oven-drying method, the moisture content in the specimens was measured to be about 8.3%. The oven-dried density measurements gave values of 432 and 506 kg/m³ for the “centre” and “periphery” specimens, respectively. In order to ensure uniform loading, the edges of the specimens were milled. After machining, the difference in the height \( h \) at different locations across the specimen was <0.01 mm. Transverse compression tests were conducted in an Instron 5567 universal testing machine with a 5 kN load cell. The tests were displacement-controlled at the rate of 1 mm/min. The specimens were compressed along the \( y \)-axis (Fig. 2) between two stiff and parallel steel plates to ensure uniform deformation at the loaded edges. For the “periphery” specimen the \( y \)-axis coincided with radial direction. No special technique was employed to quantify or eliminate friction between the specimen and loading plates. However, providing that the loading plates were well polished the friction was assumed to be rather low. The load–displacement data was logged by a computer during testing.

3.2. Strain measurements

The strain measurement system ARAMIS 1.3 M from GOM GmbH equipped with two CCD cameras (1280 × 1024 pixels) was used. The strain measurements are based on a contact-free, whole-field optical technique also known as the digital speckle photography (DSP). In this study, only one CCD camera was employed allowing for in-plane (2D) measurements. The camera was positioned perpendicular to the \( r-t \)-plane of the specimen. A reference image corresponding to the undeformed state was taken before loading of the specimen. Thereafter, the images were sampled at a frequency of 1 Hz throughout the testing. Post-processing of the DSP data was carried out using the ARAMIS software. This involved a division of sampled images into sub-images or “facets” uniquely defined in terms of spatial coordinates and grey scale contrast values. The facet size of \( 15 \times 15 \) pixels was used in the strain analysis. By means of the digital image correlation algorithm, the displacements of each facet were computed during deformation. Whole-field strains were calculated by differentiating the displacement field [7]. To facilitate image division into individual facets, a random speckle pattern must exist or needs to be applied on the specimen surface. The annual ring pattern was insufficient. Therefore, an additional pattern was applied on the surface using a black spray paint. In order to determine the accuracy of strain measurements, the noise level estimation of a computed strain field was used [8]. The specimen with applied speckle pattern was given a free-body translation in the direction of loading while taking one image before and after this translation. Since no deformation of the specimen occurred between those two stages, the DSP analysis should theoretically compute a zero-strain field. In reality, the strain field contains a noise which can be used as an estimate of strain computation accuracy. In this study, the accuracy of strain measurements was estimated to be about ±0.05% strain.

4. Finite element analysis of strain distribution

Finite element (FE) analysis was performed using the FE package ABAQUS. The 2D plane stress FE model had the size \( b = 30 \) and \( h = 20 \) mm as the test specimens, see Fig. 2. The location of the test specimens within the board (Fig. 2) and thereby, the curvature of the annual ring structure, was realized in the FE model through the parameter \( r \) defining the “pith position”. The local material axes are defined in the polar coordinate system for each element. Thereby, the FE models with \( r = 0 \) and \( r = 60 \) mm represented the “centre” and the “periphery” specimens, respectively. A square grid of \( 60 \times 40 \) elements (the element size of \( 0.5 \times 0.5 \) mm) was used in the FE analyses. The mesh convergence study showed that using even finer grid size yields identical results as for the \( 60 \times 40 \) elements mesh. FE analyses were carried out using 8-node plane stress elements (CPS8).

The boundary conditions were applied in close resemblance to the experimental setup. The displacements \( u_1 = 0 \) at the lower edge and \( u_1 = \delta \) at the upper edge of the model were applied. The exact magnitude of the prescribed displacement \( \delta \) was obtained from experimental stress–strain plots at some constant stress. The material data for European Spruce required to describe the wood orthotropy in the \( r-t \)-plane was obtained from the literature [9]. The elastic constants used in the FE analysis are listed in Table 1. The material was homogenized with no separation of earlywood and latewood properties.

5. Results and discussion

5.1. Stress–strain response

The stress–strain plots from the compression tests are shown in Fig. 3. A qualitative comparison of stress–strain plots shows distinctly different behaviours of the “centre” and “periphery” specimens under compression. The “periphery” specimen shows close to linear behaviour followed by an abrupt stress drop, associated with collapse of the earlywood in the weakest annual ring. In contrast, the stress–strain diagram of the “centre” specimen demonstrated an initially linear stage followed by a smooth non-linear region.

The apparent elastic modulus was measured from the slope of the stress–strain diagrams. For the “periphery”

Table 1

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<th>Elastic constants used in the FE analysis</th>
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<td>( E_r ), MPa</td>
<td>( E_t ), MPa</td>
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<td>1200</td>
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and the “centre” specimens it was $E_{\text{periphery}} = 1100$ and $E_{\text{centre}} = 470$ MPa, respectively. As expected, $E_{\text{periphery}}$ was close to the radial modulus $E_r$, see Table 1, reported in the literature [9]. The apparent modulus $E_{\text{centre}}$ was lower by a factor of almost 2.5 in comparison to the modulus $E_{\text{periphery}}$. In recent study by Modén [10] the radial modulus was shown to scale linearly with the density. In our study, the density ratio was only 1.17 (506 and 432 kg/m$^3$ for the “periphery” and “centre” specimens, respectively) implying that the very low value of $E_{\text{centre}}$ cannot just be explained by rather marginal density variation between the specimens. Instead, Eq. (3) and the low value for $G_{rt}$ (Table 1), provide the explanation. Despite global loading in uniaxial compression, large shear deformation from shear coupling effects contributes to the low apparent modulus of the “centre” specimen. Also note that $E_{\text{centre}}$ is significantly lower than the tangential modulus $E_t$, see Table 1. This demonstrates that the assumption of wood as isotropic in the $r$–$t$-plane with the apparent, or effective, elastic modulus considered equal to the tangential modulus [1], is thus not only rough, but also non-conservative.

Fig. 3 also presents a comparison between the experimental data and FE results. Good agreement in terms of the apparent elastic stiffness is obvious from the plots. This is encouraging since the FE model is linear-elastic and the only input parameters required for the model are four material parameters (Table 1), the size of the board in the $r$–$t$-plane and the coordinates of the pith location.

5.2. Displacement distribution

In order to investigate differences in displacement and strain distributions, those distributions are determined for the “centre” and “periphery” specimens at a nominal compressive stress of 2.3 MPa. The stress level is chosen based on the stress–strain plots (Fig. 3). At this stress, displacement differences should be detectable by DSP, and the global stress–strain response of both specimens is still expected to be close to linear-elastic.

The results from the DSP analysis in terms of the displacement $u_y$ along the $y$-axis are presented for the “centre” specimen in Fig. 4(a) and the “periphery” specimen in Fig. 4(b). For qualitative comparison, the contour plots contain isolines circumscribing the bands of equal displacement. The shape of isolines characterises a distribution of displacements and thereby, the variation of stiffness across the specimen. The displacement field in the “periphery” specimen (Fig. 4(b)) is quite uniform across the specimen except for in the areas close to the lateral edges. There, the displacements are slightly larger which could be attributed to the proximity of the free edge. Also, the annual ring pattern in these areas was not perfectly orthogonal to the loading direction so that some local shear coupling effect could be present.

Unlike in the “periphery” specimen, a non-uniform displacement field is measured in the “centre” specimen, see Fig. 4(a). The shape of isolines resemble a triangle with a vertex along the vertical symmetry line. Such a profile of the displacement field accompanied by a very high gradient in the centre and close to the upper edge, i.e. directly under the pith, does signify that the local stiffness in the central part was higher than in the adjacent lateral areas. Indeed, the material axes in the central part coincide with the loading direction and, consequently, the response is governed by the high radial modulus $E_r$. In the lateral areas, the material principle axes deviate from the loading direction due to the curvature of the annual rings. Consequently, the material response is controlled by $G_{rt}$ resulting in significantly lower local stiffness.

For comparison, the displacement fields from the FE analysis of “centre” and “periphery” specimens are presented in Fig. 4(c) and (d), respectively. Features observed in the experimental displacement plots and discussed above are also present in the FE results. Thus, a typical “triangular” displacement profile for the “centre” specimen is observed in Fig. 4(c). It is interesting to compare maximum displacement magnitudes in all four plots. The maximum displacements for the “centre” specimen are approximately factor of 2 higher than maximum displacements for the “periphery” specimen. This is in agreement with the measured factor of 2.5 difference in apparent moduli $E_{\text{centre}}$ and $E_{\text{periphery}}$. However, a comparison between the DSP and FE results shows that FE models slightly underestimate the maximum displacements. This small discrepancy is because elastic properties were obtained from the literature and not measured explicitly.

5.3. Strain distribution

Contour plots from the DSP analysis visualizing strains $\varepsilon_y$ are presented for the “centre” specimen in Fig. 5(a) and “periphery” specimen in Fig. 5(b). For the “centre” specimen, a triangular-shaped zone with low strains is observable in the central part where the material response in
Fig. 4. Comparison of measured and computed displacement fields $u_y$. The subplots (a) and (b) show the DSP data for the “centre” and “periphery” specimens; the subplots (c) and (d) show the respective results from the FE analysis. The upper edge is loaded, the bottom edge is fixed. All plots correspond to the nominal stress $\sigma_y = 2.3$ MPa.

Fig. 5. Comparison between measured and computed strain fields $\varepsilon_y$. Subplots (a) and (b) show the DSP data for the “centre” and “periphery” specimens; the subplots (c) and (d) show respective results from the FE analysis. All plots correspond to the nominal stress $\sigma_y = 2.3$ MPa.
controlled by radial stiffness $E_r$. Directly under the pith, a small area is present with high localised strains. The magnitude and high gradient of strains indicate local irreversible deformation in the form of earlywood collapse. At this stage there was no indication of non-linear deformation in the global stress–strain diagram in Fig. 3. Adjacent to the low strain central region, two regions with higher strains are present in Fig. 5(a). In these high strain regions, deformation is controlled by $G_r$. Note that strains decrease again in the regions close to the lateral edges where $E_t$ has a stronger influence on material response.

For the “periphery” specimen (Fig. 5(b)), the strain distribution is more uniform than in the “centre” specimen. A region with slightly lower strains than in adjacent areas was obtained in the central part. This unevenness in strain distribution is due to a slight curvature in the annual rings and the associated effect of shear deformation in lateral areas of the specimen. The strain fields predicted in the FE analysis are presented in Fig. 5(c) and (d). A qualitative comparison of strain distributions between experimental data and FE results demonstrates good agreement. The specific features of strain distribution in the “centre” specimen discussed above, are present in the FE results. The FE model also gave uniform strain distribution in the “periphery” specimen.

Quantitative comparison of strains obtained by the DSP and predicted by the FE analysis is presented in Fig. 6. Strains are plotted along the path schematically illustrated by the dashed line across the specimen in Fig. 5. The solid line in Fig. 6 represents the apparent global strain level for the specimen corresponding to the global stress $\sigma_y = 2.3$ MPa chosen from Fig. 3. The strain profile across the “centre” specimen is uneven and complex. In the central part of the specimen, the strain levels are significantly lower than the measured global strain. In contrast, the local strain clearly exceeds the global strain in shear-dominated regions. It can be seen that the strains along the “centre” specimen vary by a factor of 3. This finding is in agreement with results reported by Aicher [5] for a different specimen geometry. The strain profile obtained for the “periphery” board is quite even and for this case the local strains across the specimen correspond well with the global strain. The good agreement between predicted and measured strain distributions in Fig. 6 is encouraging. Despite the simplicity of the FE models (linear elasticity, homogenized material, straightforward choice of meshing and boundary conditions, data from literature) they capture both the profile of strain distribution and the strain magnitudes across the specimens. It demonstrates that conventional FE modeling with a polar orthotropic material law, is a good tool for wood modeling under transverse loading.

Stress distributions in the wood boards are also of interest. Fig. 7 demonstrates the inhomogeneous distribution of $\sigma_y$ across the “centre” specimen, according to the FE analysis. The stresses are plotted together with corresponding
The highest stress magnitudes are present in the central part of the board, below the pith, where the strains are the lowest. In shear-dominated zones, the stresses rapidly decrease by roughly a factor of 4 while strain levels increase. The association of high stress regions with low strain, and high strain regions with low stress, demonstrates the non-intuitive consequences of strong shear coupling effects. Despite the long use of wood in load-bearing applications, this phenomenon is not well-known and therefore not considered in the design of wood products. Compared with the in-plane behaviour of fiber composites, the shear coupling phenomenon in transversely loaded wood is dramatic, since $G_{rt}$ is so low compared with $E_r$ (Table 1).

6. Conclusions

The measured displacement and strain fields in the radial–tangential ($r$–$t$) plane of a wood board containing the pith region are strongly inhomogeneous. Despite application of uniform transverse compression, the local transverse strain varies by a factor of 3–4. The calculated local stress can also vary by a factor of 4. High stress corresponds to regions of low strain and vice versa. There are two closely related reasons for this inhomogeneity. The first one is the polar orthotropic material behaviour of wood in the radial–tangential ($r$–$t$) plane. This is a consequence of the annual ring structure and the differences in $E_r$, $E_t$ and $G_{rt}$. Furthermore, of the four moduli required to describe elasticity in the $r$–$t$-plane, the shear modulus $G_{rt}$ has very low value compared with $E_r$ and $E_t$. The classical shear coupling effect for composite materials is, therefore, very strong for wood. If the board contains the pith region, or regions with annual ring orientation significantly different from the board edge and loading directions, those regions show strong shear coupling effects and low stiffness. In contrast, boards with annual ring structures parallel to board edges, show little shear deformation and therefore high and uniform stiffness.

The presented strain field data from DSP demonstrate effects difficult to show by other than theoretical means. There are obviously many other combinations of wood structures and load cases where the strain distribution is strongly inhomogeneous, and application of DSP is motivated. In the present study, the DSP data correspond very closely with FE predictions. The FE model is therefore well suited for analysis of transversely loaded wood. For the purpose of elastic effects, homogenized properties are sufficient and there is no need to distinguish between earlywood and latewood behaviour.

The present study is relevant to glulam, i.e. adhesive bond performance, but also to other wood products. Strong shear coupling effects decrease stiffness and lead to inhomogeneous strain fields and, therefore, should be avoided or at least considered in design and production of high performance wood products.

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References