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An Application of 3D Fiber Angles Identified through Laser Scanning Based on Tracheid Effect

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Abstract

It is well known that the tracheid effect can be used for determination of in-plane fiber orientation on timber surfaces. Recent research indicates that out-of-plane angle, i.e. diving angle can also be determined on the basis of scanning data. This paper presents a finite element (FE) model based on knowledge of 3D fiber orientation obtained through high resolution laser scanning of a side board of Norway spruce of dimensions 24 × 95 × 2000 mm. For assessment, strain fields in the vicinity of knots due to a simulated moment load case are compared to strain fields obtained from 3D displacement measurement using digital image correlation (DIC) technique applied during a laboratory bending test. The results from simulation and measurement show good agreement regarding the strain fields. This indicates that the 3D fiber orientation model gives basis for an FE model that can be used for accurate assessment of local strains.

Keywords: diving angle, FE-model, grain angle, machine strength grading, Norway spruce, wood

Introduction

Today high resolution scanning of timber is often performed at sawmills in order to detect defects that are not allowed in applications for which the timber is intended to be used. Information regarding fiber orientation can be collected on a very local scale and such information may be used for prediction of stiffness and strength of timber, but it has not until very recently been utilized for timber strength grading. Olsson et al. (2013) presented a new method for strength grading of timber based on a combination of laser scanning, dynamic excitation and weighing of boards. The scanning of face and edge surfaces was performed using a scanner of make WoodEye® equipped with four sets of multi-sensor cameras and dot lasers. The system is based on the so called tracheid effect, where one of the principal axes of the light intensity distribution around a laser dot indicates the fiber orientation in the plane of the surface (e.g. Matthews and Beech 1976, Nyström 2003). An initial type testing procedure (ITT), see EN 14081-2, were performed and in March 2015 the method and procedure were approved by the technical group (TG1) established under the technical committee (TC 124) within the European Committee for Standardization, and the method is now available on the market. The suggested IP of the new method can predict the bending strength with high accuracy. On a sample consisting of more than 900 boards of Norway spruce of various dimensions the coefficient of correlation between IP and bending strength was $R^2 = 0.70$ (cf. $R^2 = 0.53$ obtained for dynamic longitudinal MOE vs. bending strength).
One of the simplifying assumptions made in the new method was that the angle between a wood fiber and the scanned surface, i.e. the so called diving angle, was ignored. It has been shown that the tracheid effect may be utilized for determination of the diving angle by considering the ratio between the two principal axes of the elliptically shaped light spots on the wood surface (Simonaho et al. 2004). It has not yet been investigated, however, if this can be utilized for accurate and robust high-speed identification of the diving angles on timber surfaces of e.g. spruce consisting of a mixture of early wood and late wood, knots, compression wood and so on. Nor has it been shown that fiber orientation on surfaces identified using the tracheid effect give basis for accurate 3D fiber orientation for the entire volume of a wooden board.

The aims of the present study are 1) to investigate the potential of establishing full-field 3D fiber orientation within the entire board volume using the surface fiber orientation indentified from the laser scanning; 2) to assess the significance and usefulness of such determined full-field 3D fiber information by applying it in a Finite Element (FE) model of a wooden board subjected to bending and comparison of calculated results in terms of strains with those obtained from laboratory tests with the aid of digital image correlation (DIC) system.

Material

In the study a board of Norway spruce with dimensions 24×95×2000 mm is used. The board was flat sawn taken far from the pith with annual rings almost parallel to the wide face of the board. One of the wide faces of the board was planned while the rest of the surfaces were fine sawn. The studied board has an edge knot at about the mid-length of it. Before tests, the boards had been stored in a climate room at a temperature of 20 °C and 65 % relative humidity for about eight months. After that, the average moisture content was 12.9 %.

3D modelling of fiber orientations

Scanning and calculation scheme

The board was fed through a scanner of make WoodEye® in a speed of about 75 meters per minute, by which all four longitudinal surfaces of the board were exposed to laser rays and photographed. The raw data from the scanning consists of images of elliptic laser dots. The resolution achieved regarding the laser dot information was approximately 1.3 mm in the longitudinal board direction and 4 mm in the transversal direction for each of the examined surfaces. The reason the laser dots are elliptic rather than circular in shape is that the light spread more along the tracheid cells, i.e. along the fibers, than across. The elliptical shape of the laser dots can be used to determine the full field 3D orientation on the wide faces of the board using the following five steps:

1. Finding the in-plane fiber angle. Truncation at a fixed threshold value of the light intensity was applied to determine the directions and lengths of the main axes of the elliptical spots. The direction of the longer axis is interpreted as the local direction of the fibers in the plane of the investigated surface.

2. Finding the diving angle. The ratio between the shorter and the longer axis of an elliptical light spot is used to determine the angle between the surface and the local fiber, i.e. the diving angle. The ratio was calibrated by the diving angle seen on the edge faces of the board. The ratio can however only give the absolute value of the diving angle; to find the direction of the fiber it is necessary also to determine the location of the pith of the log and the piths of knots.
3. Identifying knots and their piths. Areas where the diving angle is larger than 50° is set to be knots. When knot areas are found on both the wide faces with a distance between the centroids of the knots being smaller than 24mm (the board thickness) they are assumed to be parts of the same knot. The pith of the knot is defined as the line through the centroid of each of the knot area.

4. Identifying pith in the log. The lines through all the knots in a board are used to find the pith of the log. An estimated intersection point of all the lines representing the knot directions, as seen from the end of the log/board is set as the pith position in the log.

5. Determining the direction of the fiber angle. The fiber is then assumed to be orientated such that with respect two ends of a fiber, the end closer to the pith of the knot has a longer distance to the pith of the log.

A thorough description for the method to establish the size and orientation of the diving angle can be found in Olsson and Oscarsson (2014).

**Obtained 3D fiber angles**

An example of resulted 3D fiber orientation is shown in Figure 1. The fiber orientation that can be seen in the \(xy\)-plane, Figure 1b and Figure 1e, follow the longer main axis of the elliptic laser dots on the surface from the scanning and it is known that the result is reliable in this plane in clear wood areas (Olsson et al. 2013). The ratio, \(R\), that determines the diving angle, only affects the result in the \(xy\)-plane in the sense that the length of the lines representing the local fiber orientation are shorter in positions where the diving angle is substantial, which is in the area of the knot. In the \(xz\)-plane (c) and in the \(yz\)-plane (d) the picture depends more directly on the values of \(R\). The results show that the calculated orientation of fibers around the knot agrees quite well with what is known about the fiber orientation around/with some distance to knots in general (Shigo 1990 for example). The rule applied to decide the sign of the diving angle also works well.

**Comparison of strain fields from measurement and simulation**

**Measurement of strains**

A test is arranged as four-point bending, loaded edgewise, to apply a constant bending moment to a 570 mm long part of the board located between two point loads. The edge knot in the middle of the board, the same one as displayed in Figure 1, is placed at the tension side. Both sides of the board were photographed during loading with a DIC system (ARAMIS) to register the complete displacement field around the knot on both the wide faces. The bending test was run up to ultimate failure of the board and the time-force-displacement history was recorded all along. The ARAMIS systems work with triggers to ensure that the registration of images on both sides of the board is done simultaneously- the systems take the images and sample load signals approximately at every 15 seconds time increment and every 100 N load increment.
Figure 1- Identified 3D fiber orientation on the two wide faces of a part of the board including a knot; (a) schematic perspective image, (b) fiber orientation of the top surface in the $xy$-plane, (c) fiber orientation of both surfaces in the $xz$-plane, (d) fiber orientation of both surfaces in the $yz$-plane, (e) fiber orientation of the bottom surface in the $xy$-plane and (f) - (g) photographs of the two wide faces of the board.

**FE Model based on 3D fiber orientation**

The FE modeling is performed using the commercial software ABAQUS in which a 3D model of the board, using linear solid elements, were created. The material is defined as linearly elastic and transversely isotropic, with detailed material properties with respect to the local directions as presented in
the row with “Nominal value” in Table 1. A distinction is made between stiffness in the fiber direction and the across fiber directions but not between the tangential and the radial direction.

From the images of the board, see Figure 1, it was possible to see that there was a crack through the center of the knot already before loading. The crack goes almost perpendicularly throughout the board in the thickness, i.e. z-direction. The crack will influence the strain behavior of the board and was therefore included in the FE-model as an area with lower stiffness. The solid FE model was therefore prepared such that the elements marked with red in Figure 2 may be assigned either the nominal value for the material parameters, just as the material in all other elements of the model, or the “Reduced stiffness” defined in Table 1 in order to mimic the locally reduced stiffness caused by the crack.

In the practical handling the identified 3D fiber orientation on the two wide faces of the board as described in the previous section are sufficient inputs to represent the 3D fiber orientation model all over the board volume. The fiber angles between the two surfaces are calculated through linear interpolation between the values on the two surfaces. The data supplied consists of five parts, x-, y-, z-coordinates and two angles $\phi_{xy}$ and $\phi_{diving}$. The input files organize the position and fiber angle information in such a way that one pair of specific values of $\phi_{xy}$ and $\phi_{diving}$ are allocated for each position (x, y, z) on the board surfaces.

Table 1 - Material parameters adopted in the FE model, where 1, 2 and 3 correspond to the tangential, longitudinal and radial directions of the fibers, respectively.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>$E_1$ [MPa]</th>
<th>$E_2$ [MPa]</th>
<th>$E_3$ [MPa]</th>
<th>$\nu_{12}$</th>
<th>$\nu_{13}$</th>
<th>$\nu_{23}$</th>
<th>$G_{12}$ [MPa]</th>
<th>$G_{13}$ [MPa]</th>
<th>$G_{23}$ [MPa]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nominal value</td>
<td>533</td>
<td>14300</td>
<td>533</td>
<td>0.015</td>
<td>0.45</td>
<td>0.45</td>
<td>1000</td>
<td>50</td>
<td>1000</td>
</tr>
<tr>
<td>Reduced stiffness</td>
<td>5.3</td>
<td>143</td>
<td>5.3</td>
<td>0.015</td>
<td>0.45</td>
<td>0.45</td>
<td>10</td>
<td>0.5</td>
<td>10</td>
</tr>
</tbody>
</table>

Figure 2 - The FE-model of the board with a possibility of introducing an initial crack. The material property of the red part is defined either by nominal value or reduced stiffness in Table 1.

Strains calculated based on 3D fiber orientation

Figure 3 shows normal strains in the longitudinal board direction according to (a-b) a FE model and simulation employing only the nominal material stiffness properties (cf. Table 1); (c-d) the DIC results; (e-f) the FE model with reduced material stiffness, i.e. with consideration to the initial crack in the knot. The left images of Figure 3, i.e. (a), (c) and (e), display strains for the pith side surface and the right images, i.e. (b), (d) and (f), displays the strains for the bark side surface. The FE models employed had an in-plane element size of 1.5×1.5 mm but the strains displayed in Figure 3 (a, b, e and f) are average values over surrounding areas of 6×6 mm².

Comparing the different strain plots of Figure 3 there is an obvious resemblance between the results from the FE models based on the fiber orientation model and the result from the DIC measurement, regarding
both the strain pattern and the strain levels. The FE model that ignores the initial crack in the knot (a-b) gives large positive strains over an area slightly larger than the knot itself. Of course, this is due to the low stiffness in positions where fibers are directed perpendicularly to the longitudinal direction of the board. Thus, locally this model gives a different strain pattern compared to the other strain plots. In this respect the FE model that takes the crack into account (e-f) shows better agreement with the DIC results (c-d). Note, however, that the crack only causes a local effect. Apart from an area only slightly larger than the knot there is hardly any difference between (a-b) and (e-f). Both FE models and the DIC images show concentrated positive strains just below the knot, both to the left and to the right of it. Also, the concentrated negative strain on the compression edge of the board, slightly to the right of the knot on the pith side surface (caused by a hole visible in Figure 1a) can be distinguished in (a), (c) and (e). However, the FE model also shows a few local strain concentrations, far away from the knot; those are not shown by the DIC results. These can be explained by laser dots in the scanning that detect fiber deviation in single measurement position. A chip or some sawdust on one of the board surface may be the cause and, since a single laser dot represents a width of 4 mm in the vertical direction, this may explain the small strain concentrations.

Figure 3 - Longitudinal/horizontal normal strains valid for the board corresponding to a nominal stress level at the outmost fiber of the board about 33MPa obtained from (a-b) a FE model considering only the nominal material stiffness properties, (c-d) the DIC results and (e-f) the FE model with reduced material stiffness, i.e. with consideration to the initial crack in the knot. Left images (a), (c) and (e) display strains for the pith side surface. Right images (b), (d) and (f) display the strains for the bark side surface.

Figure 4 shows, for the same load case as for Figure 3, normal strains in the transversal board direction, i.e. vertical direction, according to (a-b) the DIC results; (c-d) the FE model with reduced stiffness, i.e. with consideration to the initial crack in the knot. Figure 5 shows the corresponding shear strains. As for the normal strains in longitudinal direction there is, both for transversal normal strains and for shear strains, an obvious resemblance between the results from the FE model and the result from the DIC measurements. Regarding transversal normal strains, see Figure 4, large positive strains appear just beneath the knot on all the plots. Bending tests of sideboards with a knot on the tension side also show that the failure mode in most cases consists of the development of a horizontal crack beneath the knot that propagate along the fiber direction, i.e. almost horizontally, on both sides of it.
Figure 4—Transversal/vertical normal strains valid for the board corresponding to a nominal stress level at the outmost fiber of the board about 33MPa obtained from (a-b) the DIC results and (c-d) the FE model with reduced material stiffness, i.e., with consideration to the initial crack in the knot. Left images, (a) and (c), display strains for the pith side surface. Right images, (b) and (d), display the strains for the bark side surface.

Figure 5—Shear strains valid for the board corresponding to a nominal stress level at the outmost fiber of the board about 33MPa derived from (a-b) the DIC results and (c-d) the FE model with reduced material stiffness, i.e., with consideration to the initial crack in the knot. Left images, (a) and (c), display strains for the pith side surface. Right images, (b) and (d) display the strains for the bark side surface.

**Discussion and Conclusions**

A modelling scheme for the 3D fiber orientation of the entire volume of a side board of Norway spruce, based on data from dot laser scanning and utilization of the tracheid effect, was presented. The diving angle was determined based on the ratio between the shorter and longer axis from the tracheid effect. The direction of the diving angle was set to follow the direction of the pith of the knot in question defined as areas where the diving angles were larger than 50°. The fiber orientation derived in areas around knots seems to be in fair agreement with the actual fiber orientation seen on such surfaces.

The 3D fiber orientation models established were conveniently integrated with the FE model using the software ABAQUS. The model was used to simulate four point bending test on the board with transversing knots located at the tension edge. The same board as evaluated and modelled with respect to their individual fiber orientation in 3D were also tested in four point bending in laboratory and strains on the wide faces were estimated using DIC technique which enabled comparison to strains calculated on the
basis of the FE model including fiber orientation information. Comparisons of strain fields, i.e. normal strains in longitudinal and transversal board direction and shear strains, from the measurement and simulations showed close agreement regarding both strain patterns and strain levels. The large positive normal strains in direction perpendicular to grain that occur beneath a knot located on the upper/tension edge of the board, and normally cause fracture in the board subjected to bending, were well captured by the FE model. Also, small defects in the wood, e.g. a very small hole on one of the wide faces rather close to the edge in compression, caused local strain concentrations that were clearly detectable both on the strain plots from the laboratory measurement and from the simulations.

In conclusion the modelling approach presented using the 3D fiber orientation information shows promising results. It can be used for accurate calculations of strain fields and it could be used also for assessment of stresses, provided that sufficient knowledge of the stiffness parameters of wood material in direction along and across fibers is available.

Further work would be (1) to make the modelling scheme more general, i.e. to make it able to handle wooden boards also from the centre part of logs and not only side boards, (2) to address the fiber orientation in the transit zone between knots and clear wood and (3) to evaluate the usefulness of the fiber orientation model on more challenging applications such as prediction of strength and failure modes of timber.

References

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