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CHARACTERIZING INFLUENCE OF LAMINATE CHARACTERISTICS ON ELASTIC PROPERTIES OF CROSS LAMINATED TIMBER

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ABSTRACT: Properties of CLT panels are influenced by the properties of their layers and the layer properties are in turn influenced by the structural characteristics of the laminate material. In order to realize the mechanical property potential of CLT panels it is necessary to understand the effects of laminate properties on the performance of the final product. This paper presents the approach and outcomes of an on-going study dealing with the evaluation of material and structural characteristics of laminates and their effects on overall characteristics of CLT using modal testing. Characteristics of "homogenised" layers and CLT panels were evaluated using modal and static testing. The suitability of test methods was established for single-layer panels and CLT panels. Relationships between overall single-layer properties and laminate characteristics were established. Differences in CLT properties calculated by different calculation models were discussed.

KEYWORDS: Cross laminated timber (CLT), Modal testing, Elastic properties, Laminate characteristics

1 INTRODUCTION

In order to compete against other building materials, like steel and concrete, it is necessary for the timber industry to develop new and improve existing engineered wood products. Cross laminated timber (CLT) is an engineered wood product made from layers of timber boards. The layers are typically glued together at 90 degrees to adjacent layers. As a result of the alternating grain direction of the adjacent layers, CLT shows not only material dependent anisotropy, but also structural anisotropic behaviour. The layered glue-up forms a stiff and strong plate-like structure that makes CLT suitable for use in shear wall and flooring applications, similar to reinforced concrete slabs. CLT shows potential for two-way bending action and therefore an economical use in floor construction. Current standardized design procedures for CLT under out-of-plane loading however are often based on one-dimensional beam models. This does not utilize the full potential of CLT panels. Two-way plate models based on finite element (FE) analysis or advanced laminated plate theory can predict normal and shear stress distributions, as well as deflection of CLT panels under transverse loading. These models have the potential to be adopted for CLT design use. The structural properties of CLT are strongly influenced by the lay-up, the thickness and the material properties of the layers in the structure. The structural characteristics of CLT panels are usually fairly easy to include in these models. A major challenge for using these models is the determination of input properties for individual layers, especially in the direction transverse to the grain of the laminates. The structural properties of a layer are mainly influenced by the elastic properties of the used laminates as well as the laminate aspect ratio (width to thickness), their growth ring orientation and the existence of edge-gluing between adjacent laminates. The objective of this study was to develop relationships between layer characteristics and equivalent elastic properties for input into two-way plate models. Furthermore differences in CLT property calculation models are evaluated.

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2 METHODOLOGY

2.1 MATERIAL ASPECTS

Wooden boards, mainly spruce with various growth ring patterns were conditioned to a moisture content of 13%. To facilitate further processing, all boards were sized to constant dimensions after conditioning. The boards were cut to a length of 1500mm, a width of 128mm and were planed to a thickness of 19mm. In order to maintain the achieved moisture content during further processing and testing, the boards were stored in a conditioning chamber maintained at 20°C and 65% relative humidity.

2.2 EVALUATION OF LAMINATE CHARACTERISTICS

The modulus of elasticity (E) of boards and their shear modulus (G) were determined by use of a modal testing technique as described in [1, 2]. In order to obtain the elastic characteristics of the boards, the first and second natural frequencies in free-free support condition were determined. Free-free support conditions were achieved by suspending the test specimen with springs. Based on the laminate natural frequencies, their dimensions and density, elastic modulus of elasticity (E) and the shear modulus (G) were evaluated in an iterative process. All boards were labelled and their dimensions, density, elastic properties and natural frequencies were documented.

2.3 LAMINATE GROUPING AND LAYER GLUING

The boards were sorted into different groups with similar characteristics, namely mean elastic properties (E and G values) and growth ring orientation (flat-sawn, quarter-sawn and about 45°). Laminates were cut out of the boards. In order to investigate the influence of laminate width on layer characteristics, three laminate widths were included, 120mm, 76mm and 32mm, while keeping the thickness constant. All laminates cut from one group had the same width and thickness. Between the different groups the aspect ratio (width to thickness) varied: 8:1, 5:1 and 2:1. Boards with major defects were either excluded, exchanged or cut to a smaller laminate width in order to allow removal of the defects or to distribute the defects over the final layer.

The boards within a group were glued together to form fully-edge-glued (FEG) and semi-edge-glued (SEG) single-layer panels using a two-component structural polyurethane adhesive. The order of laminates within a layer was randomly chosen. To minimize surface distortion and cupping, the laminates were edge-glued together with alternating pith location. In case of moisture content changes the alternating pith location of adjacent laminates led to less surface distortion and cupping of the single-layer panel and therefore better dimensional stability. FEG layers were formed by laminates glued together over the whole side edges of the laminates. SEG layers were used to simulate non-edge-glued layers in CLT. The SEG layers were formed by laminates glued together with a minimum local glue spots. The minimum local glue area was needed to enable the structure to be tested as a layer during the single-layer stage. Glue was applied at the ends and the centre of the layers over a length of about 4% of the total length of the layer.

The grouping of the laminates by elastic modulus, shear modulus, aspect ratio and growth ring pattern, provided the basis for the investigation of the influence of these laminate characteristics on the layer overall characteristics. Minimizing the variation of the selected properties within each group and therefore within each layer led to "homogenised" layers with similar laminate characteristics.

After the gluing process the layers were re-sized to uniform dimensions. FEG layers were re-sized to a length of 1220mm, a width of 588mm and a thickness of 15.4mm. SEG layers were re-sized to a length of 1460mm, a width of 588mm and a thickness of 15.8mm. The additional length of the SEG layers accounted for the local glue spots. By increasing the panel length the glue spots could be cut off after the single-layer stage. The difference in thicknesses of the two layer types resulted from tolerances of the sanding machine that was used to plane the panels. In total 55 FEG layers and 54 SEG layers were produced.

2.4 EVALUATION OF LAYER CHARACTERISTICS

The single-layer plate specimens were tested to determinate their elastic parameters using modal test methods by [3, 4], and static tests based on [5, 6]. In the modal testing, the frequency response function (FRF) of each pair of impact and response locations was calculated using data measured by an accelerometer and an instrumented impact hammer. Signals from these sensors were recorded by a spectrum analyser with a built-in analysis software to calculate FRF. The natural frequencies and the corresponding mode shape information can be extracted manually from the various FRF's calculated from different locations on the surface of a plate specimen. More details on modal testing can be found in [7].

The plate modal testing method described in [3] was initially developed for the determination of the orthotropic elastic constants of plywood boards. The elastic modulus in face grain direction (E_{11}), the elastic modulus perpendicular to the face grain direction (E_{22}), and the in-plane shear modulus (G_{12}) are determined by the measurement of three natural frequencies using three frequency equations. In the method, the plate-shaped specimen is vertically erected, simply supported along the bottom edge with the other three edges free. Simply supported boundary conditions were achieved by clamping the specimen edge with two steel pipes. The test setup can be seen in Figure 1. The elastic properties were calculated using the equations given in [3] for the three selected frequencies. In this study the natural frequencies f_{11}, f_{12} and f_{31} were selected. In theory, any 3 natural frequencies can be used. However the sensitivity of calculated results is dependent on the values of the elastic properties and specimen geometry. The natural frequencies used in the calculation were selected based on a sensitivity study.

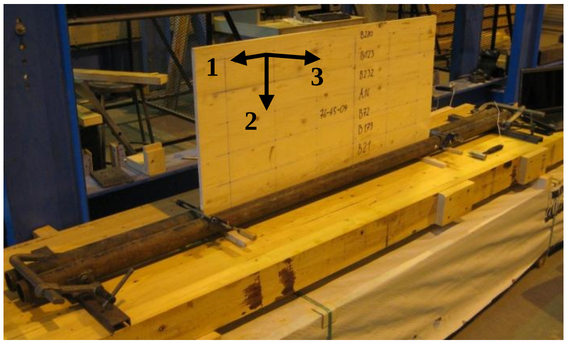

Figure 1: *Test setup for modal tests by [3]*

The method by [4] is based on free-free boundary conditions and has no closed form solution. Free-free boundary conditions were achieved by suspending the plate from a rigid structure with springs in a vertical position. The test setup can be seen in Figure 2. The natural frequencies and the related mode shapes of the single-layer panels were determined.

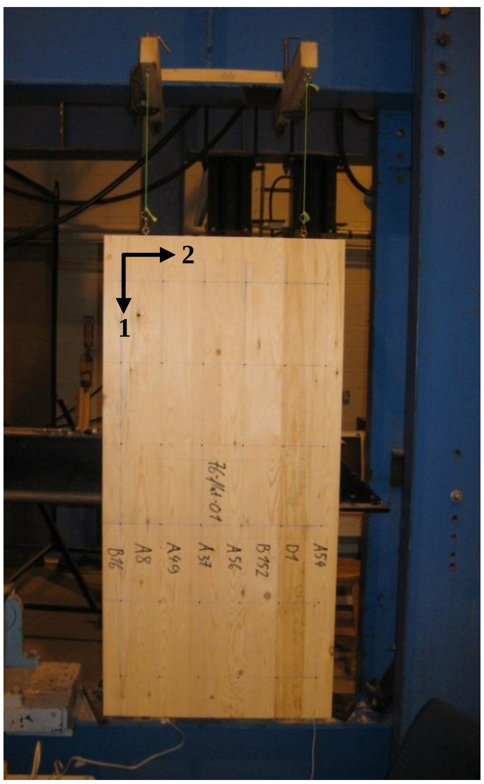

Figure 2: *Test setup for modal tests by [4]*

In this method the elastic constants E_{11}, E_{22} and G_{12} are determined in an iterative process using FE analysis. In the process, the three elastic constants were adjusted successively until experimental and analytical natural frequencies and related mode shapes ($f_{1,1}$, $f_{2,0}$ and $f_{0,2}$) matched. A FE model of the test setup used was developed. The single-layer panel was modelled as a shell element, the free-free boundary conditions were achieved by two supports at the locations of the strings. The supports allow movement in direction 2 (minor axis) and 3 (out-of-plane) and restraints the in-plane movement in direction 1. The FE model can be seen in Figure 3. In addition the material properties E_{11}, E_{22} and G_{12} determined by the method by [3] were used in the FE model for [4] and the calculated natural frequencies and mode shapes were compared with the natural frequencies and mode shapes from the results of the tests under free-free support conditions.

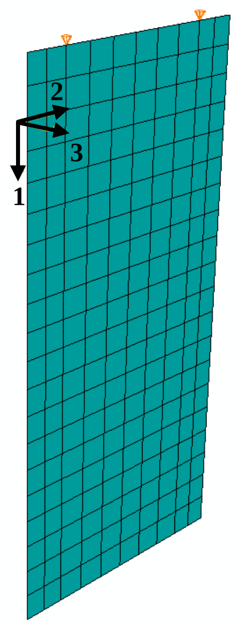

Figure 3: *Finite element model for test setup by [4]*

Static 3-point bending tests in accordance with [5] were performed in order to evaluate the E_{11} values of FEG and SEG plates. The E_{11} values for both layer types were evaluated at a span of 1100mm and a displacement rate of 8mm/min. Further 3-point bending tests were performed to confirm the E_{22} values of the FEG layers. Bending tests for the evaluation of the E_{22} values of the SEG layers were not conducted since the local spot gluing of the SEG layers did not provide enough stability to perform bending tests perpendicular to the grain. The E_{22} values for the FEG layers were evaluated at a span of 500mm and a displacement rate of 0.75mm/min. Due to geometry limits of the press, the single-layers had to be cut in half to perform the bending tests for the E_{22} value evaluation. In both test setups the specimens were supported over the full width by simple supports that allowed free rotation. The load was distributed at the centre of the span over the full width of the specimen by a squared hollow aluminium section. The deflection was measured by two linear variable differential transformers (LVDTs), located at the centre of the span and 100mm in from the either side edges. The two measurements from the LVDTs were averaged for the calculation of the E values. Figure 4 shows the test setup for the evaluation of the E_{11} values.

Figure 4: *Bending test setup for E_{11} value evaluation*

Furthermore static twisting tests in accordance with [6] were performed on selected FEG layers to evaluate the in-plane shear modulus, G_{12}. A total of 18 panels (initially from 9 full-size panels) with different aspect ratio and growth ring orientation combinations were tested. In the test setup the square panels were supported on two diagonally opposite corners by ball bearings and were loaded on the other two diagonally opposite corners, as shown in Figure 5. The span of the supports was 400mm and the distance between the loading points was 400mm. The tests were performed at a displacement rate of 3mm/min. According to [6] the deflection of the quarter points of the diagonals between support or load points shall be measured with respect to the centre point. Therefore the deflections at the centre of the panel and at the quarter points of the diagonal between support or load points were measured by two LVDTs. After a test, the LVDT at a quarter point was moved to another quarter point and the test was repeated until the deflection of all four quarter points have been measured. The relative deflection of the quarter points with respect to the centre of the panel was determined. The absolute relative deflections of the quarter points were averaged and used for the determination of the G_{12} values.

The results from the modal test method were compared with each other and with the results from the static tests. The analysis of the test data led to the development of relationships between laminate characteristics and elastic properties of the single layers.

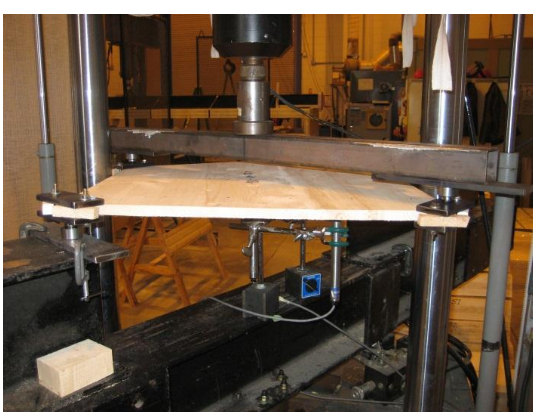

Figure 5: *Twisting test setup for G_{12} value evaluation*

2.5 CLT GLUING

After the completion of the single-layer test phase the single-layers were face-glued to form square 3-layer CLT panels. The 3-layer CLT panels were generally formed from layers within the same group, namely the same aspect ratio, growth ring orientation and edge-glue situation. The CLT panels were also formed in a symmetrical lay-up where the outer layers are from the same full-size single-layer and the centre layer is from a different full-size panel. Even in a non-edge-glued CLT production, it is reasonable to assume that due to the high applied pressure in manufacturing a certain quantity of glue from the face-gluing will squeeze into the gaps between adjacent laminates. In order to avoid such accidental edge-gluing in the SEG layers the gaps between adjacent laminates were taped off with an acrylic adhesive coated polypropylene tape, commonly used in joint sealing of house wrapping material. The same glue that was used for the edge-gluing process was used for the face-gluing. A glue spread rate of $250g/m^2$ per glue line and a pressure of $1N/mm^2$ was applied. Within the recommended work time of 45 minutes four 3-layer CLT panels were produced at the same time. The pressure was maintained for the first 3 hours of the curing process. After the pressure release the CLT panels were stored in the conditioning chamber for at least another 12 hours before further processing. A total of 19 FEG layer based-, 19 SEG layer based CLT panels has been produced at the time of writing this paper.

2.6 EVALUATION OF CLT CHARACTERISTICS

After the face-gluing process the 3-layer CLT panels were re-sized to a length and width of 570mm. The properties of the 18 selected CLT panels were evaluated in a similar way as the single-layer panels using the modal test method by [4], and static 3-point bending tests based on [5]. The selected 18 panels include one panel of each combination of aspect ratio, growth ring orientation and edge-gluing situation.

In the modal test method by [4] the 3-layer CLT panels were tested in free-free boundary conditions. The natural frequencies and related mode shapes were determined. The 3-layer CLT panels were modelled in a FE program in two different ways. First, the panel was modelled as a solid cross-section where material properties (E_{11}, E_{22}, G_{12}) were adjusted in an iterative process until the natural frequencies and mode shapes ($f_{1,1}$, $f_{2,0}$, $f_{0,2}$) from the FE analysis match the measured values (FE model: "iteration solid"). Second, the panel was modelled as a 3-layer panel where material properties (E_{11}, E_{22}, G_{12}) were adjusted in an iterative process until the natural frequencies and mode shapes ($f_{1,1}$, $f_{2,0}$, $f_{0,2}$) from the FE analysis match the test results. In order to simplify the iterative process it was assumed that the material properties within a global direction of the 3-layer CLT panel changed by the same percent. As a basis for this percentage change the corresponding single-layer properties were used. For example the material properties in the global direction of a 3-layer CLT panel were changed by X% in the primary direction, Y% in the secondary direction and Z% for the in-plane shear properties, therefore the E_{11} values of the outer layers and the E_{22} value of the centre layer were changed by X%, the E_{22} values of the outer layers and the E_{11} value of the centre layer were changed by Y%, and the G_{12} values of all three layers were changed by Z% (FE model: "iteration 3-layer"). Comparison of results from the third and fourth method will allow us to evaluate the validity of using FE model to predict CLT bending properties and how the results would be influenced by methods of obtaining input properties.

Static 3-point bending tests in accordance with [5] were performed in order to evaluate the E_{11} and the E_{22} values of the 3-layer CLT panels. The test span was 500mm and the displacement rate was 0.5mm/min. In both test setups the specimens were supported over the full width by supports that allowed free rotation. The load was distributed at the centre of the span over the full width of the specimens by a squared hollow aluminium section. The deflection was measured by two linear variable differential transformers (LVDTs), located at the centre of the span and 100mm in from the either side edges. The two measurements from the LVDTs were averaged for the calculation of the E values.

3 RESULTS AND DISCUSSION

At the time of writing this paper the elastic properties, E_{11}, E_{22} and G_{12}, of both FEG and SEG single-layer panels have been measured using modal testing method [3, 4]. Static 3-point bending tests based on [5] have been performed to evaluate E_{11} and E_{22} for all single-layer panels. In addition static twisting tests based on [6] have been performed on selected panels to evaluate G_{12}. The elastic properties, E_{11}, E_{22} and G_{12}, of the 18 3-layer CLT panels were also measured using modal testing method by [4]. Static 3-point bending tests based on [5] have been performed to evaluate E_{11} and E_{22} for these 3-layer CLT panels.

3.1 SINGLE-LAYER PANEL RESULTS

The evaluated E_{11} values of both single-layer panel types, FEG and SEG, are compared with the corresponding average laminate E ($E_{average}$). The E_{22} values of the single-layers could not be compared in this way since no comparable data from the laminates exists.

Figure 6 shows a comparison of the results from the various combinations of laminate aspect ratio and growth ring orientation for the FEG single-layer panels. The increases in E_{11} value with respect to the $E_{average}$ value for each layer from the three different test methods by [3], [4], and [5] are presented by three adjacent bars within a set. The left, middle and right bar within a set represents the results based on [3] [4] and [5] respectively for a specific single-layer panel specimen. The black markers indicate the $E_{average}$ values of the corresponding layer. In general, the results from the three test methods are fairly close to each other. Results based on [3] (modal testing with one edge simply supported) tend to show the lowest value, while results based on [5] (static bending) show a tendency to be the highest for a panel. It can be seen that laminates with the smallest aspect ratio (width 32mm) (Figure 6 a)), a flat growth ring orientation (Figure 6 d)) or a growth ring orientation of about 45° (Figure 6 e)) show higher increase in E_{11} compared with laminate average E. For the quarter-sawn panels (Figure 6 f)) the results of the different test methods are not as close as for the other combinations. At the smallest aspect ratio (width 32mm) (Figure 6 a)), there is generally an increase for E_{11}, whereas for the other two aspect ratios (width 76mm (Figure 6 b)) and 120mm (Figure 6 c))) the trend is not clear.

The E_{11} values of the FEG panels determined by 3-point bending tests in accordance to [5] show good agreement with the ones from modal tests. The maximum, minimum and the average deviation of E_{11} and E_{22} values determined by [3] and [4] to the ones from [5] are presented in Table 1. The average difference of E_{11} determined by [3] to E_{11} determined by [5] is about -5.7%. For the E_{11} value determined by [4] the average deviation to the ones based on [5] is about -0.3%. Results for the E_{22} values of the FEG panels show a higher deviation. The average deviation from test results by [3] to the results by [5] is about 22.4%. Results from [4] show a deviation of 11.9% to the results based on [5].

Figure 7 shows a comparison of the results with regards to the various combinations of laminate aspect ratio and growth ring orientation for the SEG single-layer panels. Similar to Figure 6, the increase of the E_{11} values with respect to the $E_{average}$ value for each layer from the three different test methods by [3], [4], and [5] are presented by three adjacent bars within a set. The left, middle and right bar within a set represents the results based on [3] [4] and [5] respectively for a specific single-layer panel specimen. The black markers indicate the $E_{average}$ values of the corresponding layer. Generally the E_{11} from different methods show lower agreement compared with those for the FEG panels. Results based on [3] tend to show the lowest value, while results based on [5] always lead to the highest value for a panel and always show an increase in comparison to $E_{average}$. Besides the lower level of agreement between the different test methods other observations that can be made for the SEG panels are similar to those for FEG panels. That is smaller aspect ratio results (width 32mm) (Figure 7 a)) are more consistent with increased E_{11} across all cases whereas the trend is less clear for panels made with quarter-sawn boards (Figure 7 f)). The results based on [3] and [4] show a tendency to a decrease of E_{11} in comparison to $E_{average}$. The E_{11} values of the SEG panels determined by 3-point bending tests in accordance to [5] show a higher deviation to the results from the modal tests than the ones from the FEG panels. The maximum, minimum and the average deviation of E_{11} values determined by [3] and [4] to the ones from [5] are presented in Table 1. The average

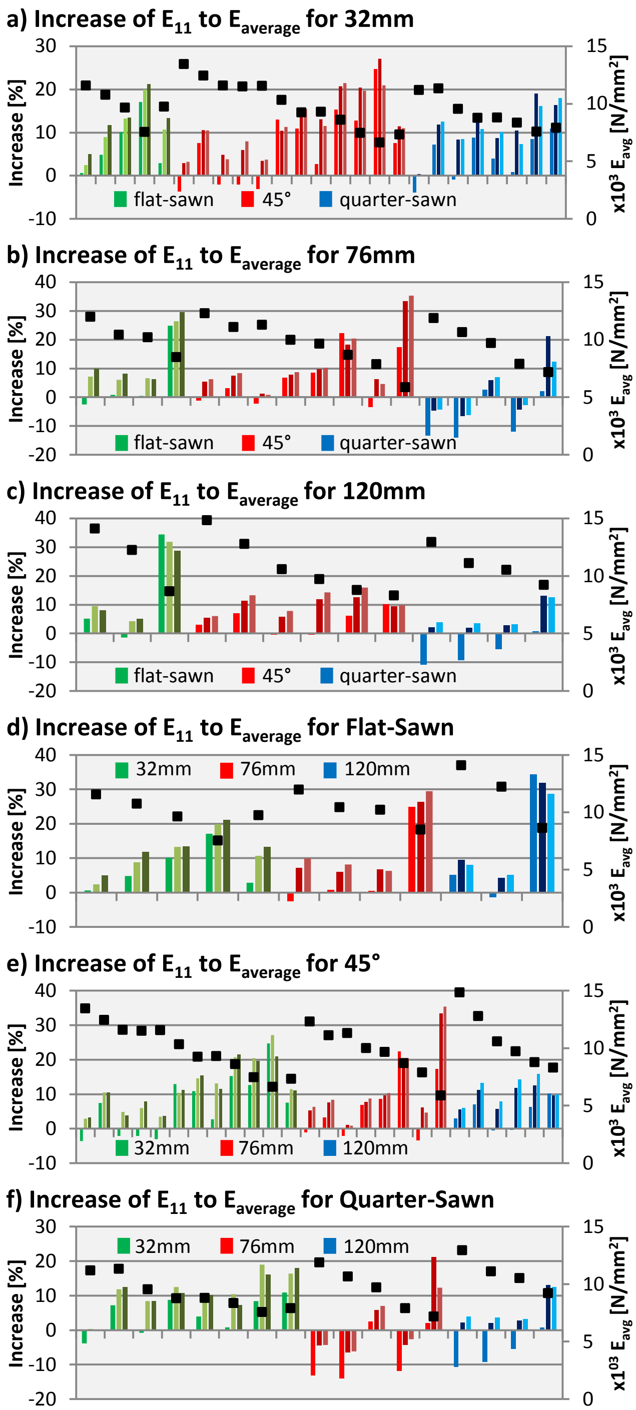

Figure 6: *Effect of laminate characteristics on E_{11} from tests [3], [4] and [5] (left to right) for FEG layers*

deviation of E_{11} values determined by [3] to the ones from [5] is about -15.7%. For the E_{11} value determined by [4] the average deviation to the ones based on [5] is -10.4%. No results could be obtained for the E_{22} values based on [5] since the layers were too flexible to be tested.

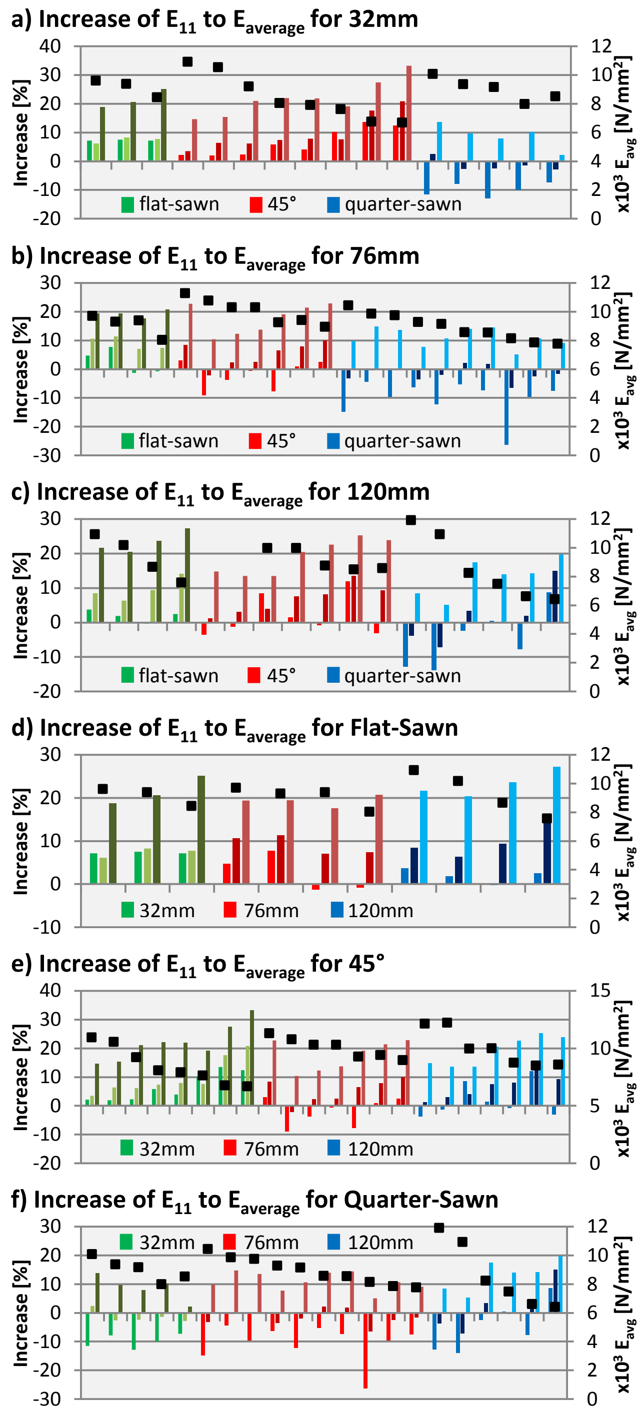

Figure 7: *Effect of laminate characteristics on E_{11} from tests [3], [4] and [5] (left to right) for the SEG layers*

In both Figure 6 and Figure 7, the layers within a group are arranged by their $E_{average}$ values, the highest $E_{average}$ values on the left decreasing to the right. The graphs for both panel types show a tendency towards a larger increase in E_{11} compared to $E_{average}$ with a lower $E_{average}$ value of the laminates in the layer.

Table 1: Difference in E by [3] and [4] compared to E by [5]

	FEG				SEG	
	E_{11}		E_{22}		E_{11}	
	[3]	[4]	[3]	[4]	[3]	[4]
Max [%]	4.4	7.9	114.9	54.5	-4.4	-4.0
Min [%]	-14.1	-3.0	-47.1	-35.2	-29.8	-13.9
Avg [%]	-5.7	-0.3	22.4	11.9	-15.7	-10.4

Figure 8 shows the difference in G_{12} values determined by modal testing methods by [3, 4] to G_{12} values determined by static tests in accordance with [6]. The black markers indicate the $G_{12,static}$ values of the corresponding layer. It can be seen that the results based on [3] show over- and under-estimation within a range -14.4% to 10.9%. All results by [4] show an underestimation of G_{12}. The values are up to -20.2% smaller than the ones based on [6]. No laminate characteristic related pattern is obvious.

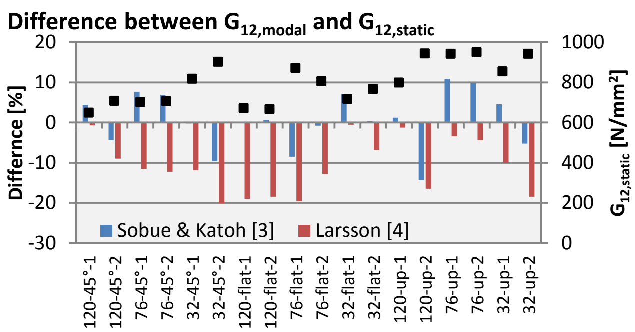

***Figure 8:** Difference between G_{12} values from modal and static tests*

3.2 3-LAYER CLT PANEL RESULTS

Eighteen 3-layer CLT panels were tested, one for each combination of aspect ratio, growth ring orientation and edge-gluing type.

Figure 9 shows the differences in the flexural stiffness in the face grain direction ($E_{11}I$) determined by different methods compared to the $E_{11}I$ values calculated ($E_{11}I_{calculate}$) by shear analogy. The $E_{11}I_{calculate}$ values are calculated by shear analogy using the single-layer properties determined by [4]. The graph gives the $E_{11}I_{calculate}$ values and shows results for both FEG layer and SEG layer based CLT panels. The black markers indicate the $E_{11}I_{calculate}$ values of the corresponding panel. The $E_{11}I$ value comparison includes values determined by the "iteration solid" FE model, values determined by the "iteration 3-layer" FE model, and $E_{11}I$ values determined by static tests based on [5]. It can be seen that the results from the different methods follow a certain trend for both FEG and SEG layer based CLT panels. The results from the "iteration solid" FE model show the closest results compared with the ones calculated by shear analogy, with results based shear analogy being higher in general than the ones based on "iteration solid" FE model. The results from the "iteration 3-layer" FE model show much higher results than all other methods, leading to unrealistic values in most cases. The results from the static tests show the lowest results for the $E_{11}I$ value evaluation with results being 33-56% lower than the calculated ones. Reasons for these lower values will be discussed in the following.

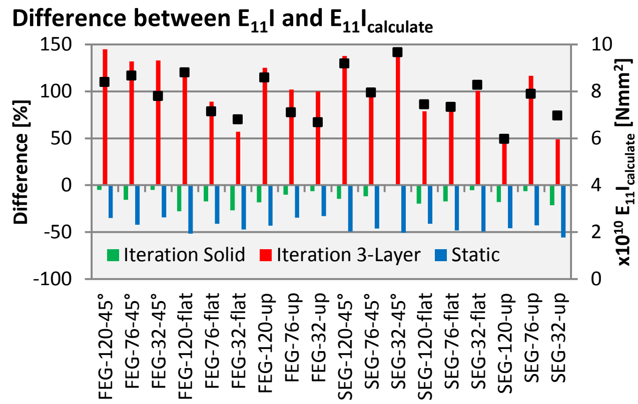

***Figure 9:** Difference between $E_{11}I$ and $E_{calculate}I$*

Figure 10 shows the difference in flexural stiffness perpendicular to the face grain direction ($E_{22}I$) determined by different methods compared to the $E_{22}I$ values calculated ($E_{22}I_{calculate}$) by shear analogy. The $E_{22}I_{calculate}$ values are calculated by shear analogy using the single-layer properties determined by [4] as input values. The graph gives the $E_{22}I_{calculate}$ values and shows results for both FEG and SEG layer based CLT panels. The black markers indicate the $E_{22}I_{calculate}$ values of the corresponding panel. The $E_{22}I$ value comparison includes values determined by the "iteration solid" FE model, values determined by the "iteration 3-layer" FE model, and E_{11} values determined by static tests based on [5]. The $E_{22}I$ value comparison shows completely different trends than the ones that were observed for $E_{11}I$. A clear difference can be observed between results from FEG and SEG layer based CLT panels. All results from the three different methods show higher values compared to $E_{calculate}I$ for the FEG layer CLT, while all results for the SEG layer CLT show lower results compared to $E_{calculate}I$. The results from the "iteration solid" FE model and the "iteration 3-layer" FE model show a good agreement between each other for both layer types. The results from the iterative methods are always higher than the results from the static tests.

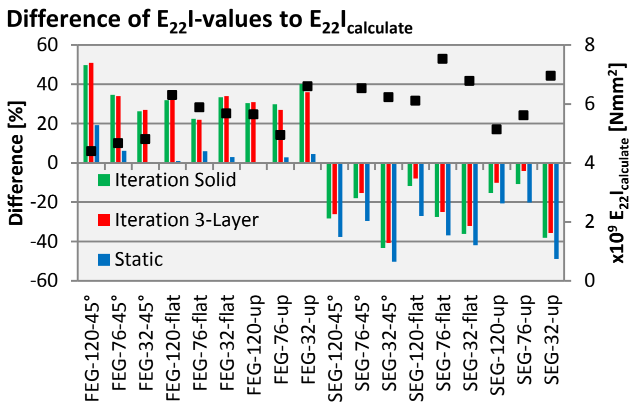

Figure 10: *Difference of $E_{22}I$ values to $E_{calculate}I$*

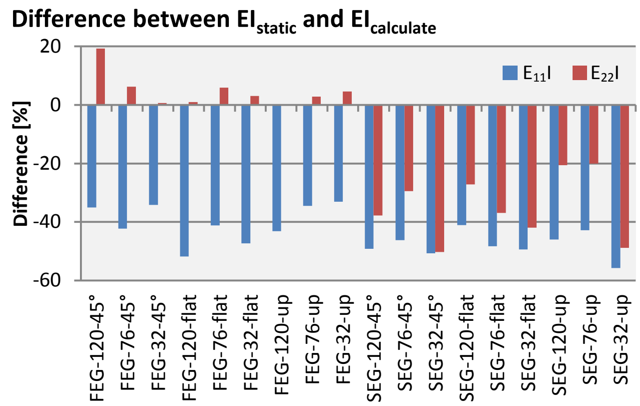

Figure 11: *Difference between EI_{static} and $EI_{calculate}$*

Figure 11 shows the difference in the EI values ($E_{11}I_{static}$, $E_{22}I_{static}$) of the 3-layer CLT panels from static bending tests based on [5] to the EI values calculated ($E_{11}I_{calculate}$, $E_{22}I_{calculate}$) on the basis of the single-layer EI values determined by [4]. For the CLT panels based on FEG layers it can be seen that the $E_{11}I$ values from static tests are 33-52% lower than those from the calculations. For the CLT panels based on SEG layers it can be seen that the $E_{11}I$ values from static tests are 41-56% lower than those from the calculations. The large difference in $E_{11}I$ values for both panel types can be described by the influence of shear deformation in the 3-point bending test with a low span-to-thickness ratio (L/h). The L/h ratio in the static tests was 10.8 for FEG layer CLT and 10.3 for SEG layer CLT. For CLT panels with L/h ratios of around 10 shear deformation of about 50% can be expected. Therefore the results shown for $E_{11}I$ values from the static tests in Figure 11 appear reasonable. In order to evaluate the influence of shear deformation and to evaluate the true $E_{11}I$ values in static tests further tests are necessary. For the FEG layer CLT it can be seen that the $E_{22}I$ values from static tests result in values that are up to 20% higher, with most values being higher by less the 6.5%, compared to the ones from the calculations. For the SEG layer CLT it can be seen that the $E_{22}I$ values from static tests result in values being lower by 20-55% compared to the ones from the calculations. The reason for this can be found in the calculation model that was used for the shear analogy. For both panel types and both directions all three layers were taken into account. For FEG layer CLT this leads to calculated $E_{22}I$ values that show good agreement with the results from static tests. The $E_{22}I$ values from the static tests are always higher than the calculated ones. For the SEG layer CLT this calculation model leads to an overestimation of the $E_{22}I$ values.

Figure 12 shows a similar comparison as Figure 11, the only difference is a change in the calculation model used for the EI values of the SEG layer panels. Here only the layers with a grain direction parallel to the test span were considered in the calculation. The stiffness properties of layers with grain direction perpendicular to the test span were considered to be zero. This is common practice in the calculation of global stiffness properties of CLT panels, especially for non-edge-glued panels. It can be seen that the trend for all $E_{11}I$ values, and for the $E_{22}I$ of the FEG CLT remains the same. The differences in the $E_{22}I$ values of the SEG layer panels are now positive with the $E_{22}I$ values from static tests being 8-51% higher than the calculated values.

Figure 13 shows that the difference between the two approaches to calculation $E_{22}I$ has a strong effect on the $E_{22}I$ value. Taking only the middle layer into account for the E22I value of the 3-layer CLT panels leads to values that are about 50% smaller than the ones calculated using all three layers.

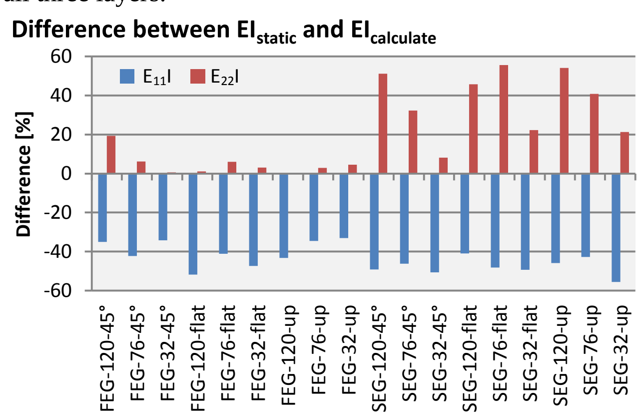

Figure 12: *Difference between EI_{static} and $EI_{calculate}$*

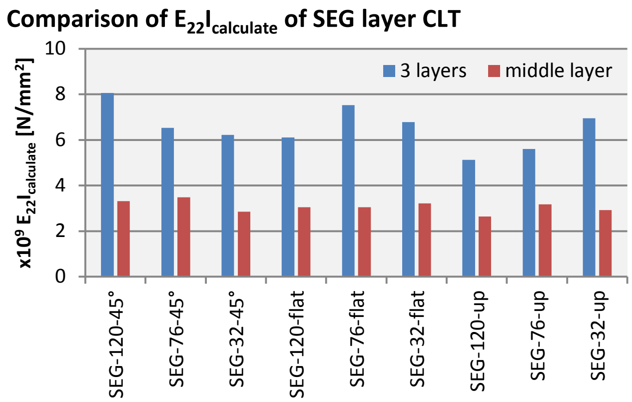

Figure 13: *Comparison of $E_{22}I_{calculate}$ of SEG layer CLT*

4 CONCLUSION

The results of all three different test methods ([3], [4] and [5]) used for the determination of the single-layer panel properties follow a certain trend among the different combinations of laminate characteristics.

For FEG single-layers following conclusions can be drawn:

- good agreement for results from all three methods ([3], [4] and [5])
- a smaller aspect ratio (32mm), flat-sawn and a growth ring orientation of about 45° lead to an increase of E_{11} compared to $E_{average}$
- the other aspect ratios (width 76mm and 120mm) show an increase of E_{11} compared to $E_{average}$ with exception of quarter-sawn panels

For SEG single-layers following conclusions can be drawn:

- the three methods ([3], [4] and [5]) exhibit lower degree of agreement compared with FEG layers
- method [5] always produces E_{11} that is larger than $E_{average}$
- flat-sawn and a growth ring orientation of about 45° lead to an increase in E_{11} compared to $E_{average}$
- all aspect ratios lead to an increase in E_{11} compared to $E_{average}$ with the exception of quarter-sawn panels

In general the test methods [3] and [4] show good agreement with the results from static tests for E_{11} and G_{12}. Method [4] seems to be more accurate for E_{11} evaluation, method [3] seems to lead to greater deviation for SEG single-layers. For G_{12} evaluation [3] seems to lead to closer results, while [4] provides a constant underestimation at a similar deviation.

For the determination of the $E_{11}I$ values by iteration it was discovered that a solid cross-section ("iteration solid") seems more accurate than the proposed iteration with 3-layers ("iteration 3-layer"). The proposed "iteration 3-layer" FE model leads to unrealistic $E_{11}I$ values. Comparing $E_{11}I$ values from static tests with $E_{11}I$ values calculated by shear analogy shows that the results from static tests are about 50% smaller than the calculated ones. This is reasonable considering the high influence of shear deformation in bending tests with specimens with an L/h ratio of about 10. Further static tests are needed to evaluate the true $E_{11}I$ values and to determine the influence of shear deformation.

For the $E_{22}I$ value evaluation the results from both iterative methods show a good agreement. Results from static tests show lower $E_{22}I$ values, but follow the same trends as the results from the iterative methods. Results of the evaluated $E_{22}I$ values are more related to the edge-gluing situation and the used approach in the shear analogy. Accounting for all layers in the calculation of $E_{22}I$ leads to higher calculated values for FEG layer based CLT but lower calculated values for SEG layer based CLT. Using only the middle layer in the calculation of stiffness property in the across face grain direction and neglecting the stiffness of the outer layers the SEG layers, leads to larger $E_{22}I$ values compared with static results. The assumption that all layers can be taken into account for the $E_{22}I$ calculation seems to be valid if the layers are edge-glued. If edge-gluing does not exist a consideration of all layers in the $E_{22}I$ calculation leads to an overestimation of the $E_{22}I$ value.

5 FURTHER RESEARCH

1. Further bending tests are needed to obtain the true $E_{11}I$ values of the CLT panels and to determine the influence of shear deformation on the obtained results.
2. An additional 4 FEG layer based- and 4 SEG layer based 3-layer CLT panels will be produced. These CLT panels will be equipped with strain gauges in the inter-layer section in selected layers and locations to gain information about the inter-layer behaviour of CLT panels in out-of-plane loading situations.
3. After the 3-layer CLT panel tests have been completed the certain CLT panels will be converted into 5-layer CLT panels by adding two additional outer layers. The 5-layer CLT panels will be tested in static bending tests and using modal testing methods by [3, 4].
4. In addition to the two single-span bending tests two-way bending tests with all edges are supported will be performed for both, the 3- and 5-layer CLT panels.

Results from the 3- and 5-layer CLT tests will be compared with results from FE analysis using the evaluated global CLT properties and the single-layer properties. This will help to evaluate relationships between material properties and appropriate input properties for FE analysis.

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