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INFLUENCE OF BOUNDARY CONDITIONS IN MODAL TESTING ON EVALUATED ELASTIC PROPERTIES OF MASS TIMBER PANELS

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ABSTRACT: Cross laminated timber (CLT) has the potential to play a major role in timber construction as floor and wall systems. In order to meet specific design needs and to make the use of CLT more effective, property evaluation of individual CLT panels is desirable. Static tests are time-consuming and therefore costly, and for massive products such as CLT hard to implement. Modal testing offers a fast and more practical tool for the property evaluation of CLT and timber panels in general. Elastic properties of "homogenised" single-layer timber panels and scaled CLT panels were evaluated using modal testing methods with different boundary conditions (BCs). The results were compared with results from static test. This paper presents a comparison of different boundary conditions in modal testing in terms of accuracy, calculation effort and practicality.

KEYWORDS: Cross laminated timber (CLT), Modal testing, Boundary conditions, Elastic properties

1 INTRODUCTION

Cross laminated timber (CLT) is an engineered wood product made from layers of timber pieces. Due to the layered glue-up with alternating grain directions of adjacent layers, CLT forms a stiff and strong orthotropic plate structure. The stiff structure shows high potential in shear wall and floor applications, construction elements that are dominated by reinforced concrete in large structures. CLT has the potential to replace reinforced concrete in these applications up to a certain point. Unlike reinforced concrete elements, which are designed based on the structural needs, CLT elastic properties used for design purposes are based on the build-up of the panels and on assumed elastic constants of the component material. The elastic properties that are mainly needed in CLT design are the modulus of elasticity parallel to the grain of the outer layers (E_{11}), the modulus of elasticity perpendicular to the grain of the outer layers (E_{22}), and the in-plane shear modulus (G_{12}). The elastic properties of individual CLT panels can be evaluated by static tests. From these static test methods only one elastic constant can be evaluated at a time, for some of them multiple tests are needed, which makes static tests time-consuming and therefore costly. Static test methods also have an inherent risk of causing structural damage within the panel during testing. Moreover for massive panels, it is difficult in terms of practicality to test the full-size panels from production lines, using static test methods. Modal testing methods show potential to be adopted for non-destructive evaluation of elastic properties of CLT. In modal testing, the structure is exposed to a controlled excitation and the natural frequencies are measured. The natural frequencies and their order within a response spectrum are influenced by the dimensions and the density of the structure as well as the boundary conditions (BCs) and the elastic properties of the structure. Therefore the elastic constants of a structure can be evaluated if the structure's dimensions, density, the BCs and the response spectrum are known. The dimensions and the BCs can be well controlled for a test setup. The mass and therefore the density of a full-scale panel can easily be evaluated without significant costs or delay of the manufacturing process. In general it is possible to determine the three main elastic constants (E_{11}, E_{22}, and G_{12}) of the structure.

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While modal testing appears to be a more efficient test method compared to static testing, especially for massive elements, research is still required before the modal test can be adopted widely. One technical challenge is the choice of the BCs. As mentioned before, BCs affect the natural frequencies and the response spectrum of a structure in terms of damping. Also, some BCs offer close-form solutions for the property evaluation while others require the use of cumbersome iterative numerical procedures. Furthermore, different BCs show different levels of practicality. The objective of this study is to compare modal testing methods with different BCs in terms of accuracy of evaluated elastic properties (E_{11}, E_{22}, and G_{12}), calculation effort and to give a comparative conclusion on the practicality of applying modal testing to evaluate full-size CLT panels.

2 METHODS

2.1 SPECIMEN DESCRIPTION AND GENERAL PROCEDURE

Single-layer panels were produced from conditioned (moisture content 13%) laminates. The used material was mainly spruce. Before the manufacturing of the single-layer panels all laminates were tested in a modal testing method with free-free BCs by [1, 2]. The laminates were grouped based on their elastic properties, namely modulus of elasticity (E) and shear modulus (G), and their growth ring orientation (flat-sawn, quarter-sawn and about 45°). Laminates within a group had similar elastic properties (E, G) and growth ring orientation. The single-layer panels were formed from these “homogenised” groups. All laminates within a single-layer were sized to the same aspect ratio (width to thickness). All single-layers had the same constant thickness. Three different aspect ratios were chosen 8:1, 5:1 and 2:1 at a constant thickness of 15.4mm. The single-layer panels were formed by laminates glued together over the whole length of the laminates using a two-component structural polyurethane adhesive. The order of laminates within a layer was random. To minimize surface distortion and cupping, the laminates were edge-glued together with alternating pith location. In case of changes in the moisture content the alternating pith location of adjacent laminates led to less surface distortion and cupping of the single-layer panel and therefore better dimensional stability. In order to maintain the achieved moisture content during further processing stages, the material was stored in a conditioning chamber with a constant climate.

The three main elastic constants of the single-layer panel, namely the modulus of elasticity parallel to the grain (E_{11}), the modulus of elasticity perpendicular to the grain (E_{22}) and the in-plane shear modulus (G_{12}), have been evaluated using different test methods. The results of the different test methods were compared with each other.

The single-layers were face-glued to form 3-layer panels after the single-layer panel tests were completed. The 3-layer CLT panels were formed from layers within the same group, namely the same aspect ratio, and growth ring orientation. The CLT panels were also formed in a symmetrical build-up where the outer layers were from two halves of a full-size single-layer and the centre layer was from a half of a different full-size panel. The same glue that was used for the edge-gluing process was used for the face-gluing. A glue spread rate of $250 g/m^2$ per glue line and a pressure of 1MPa 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. The elastic constants, namely the modulus of elasticity parallel to the grain of the outer layers (E_{11}), the modulus of elasticity perpendicular to the grain of the outer layers (E_{22}), and the in-plane shear modulus (G_{12}), of the CLT panels were evaluated using the same test methods previously used for the single-layer panels. The results of the different test methods are compared and discussed below.

2.2 MODAL TESTING METHODS

The elastic properties of the single-layer panels and the CLT panels were evaluated using modal testing methods with different BCs. In 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 [3].

The modal testing method described in [4] 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 simultaneously by the determination of three natural frequencies. In the method, the plate-shaped specimen is vertically erected. The panel is simply supported along the bottom edge while the other edges have free BCs (FFFS). Simple support BC was achieved by clamping the specimen edge with two steel pipes. The test setup can be seen in Figure 1.

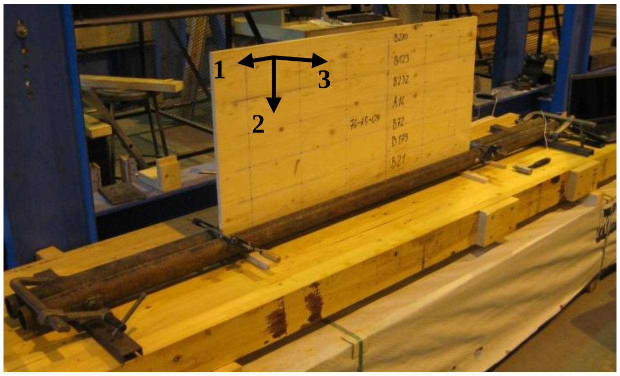


Figure 1: *Test setup for modal tests in FFFS BCs*

The elastic properties were calculated using the equations given in [4] for the three selected natural 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 values of the elastic properties and specimen geometry. The natural frequencies used in the calculation were selected based on a sensitivity study. A total of 55 single-layer panels were tested with the FFFS BCs.

The method by [5] is based on free-free BCs (FFFF). The approach has no closed form solution. FFFF BCs were achieved by suspending the plate from a rigid structure with springs in a vertical position. The natural frequencies and the related mode shapes of the panels were determined. The test setup for a single-layer panel can be seen in Figure 2.

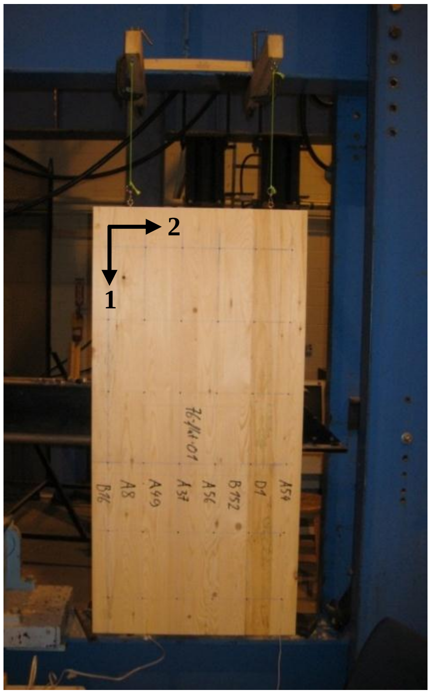


Figure 2: *Test setup for modal tests in FFFF BCs*

In this method the elastic constants E_{11}, E_{22} and G_{12} are determined in an iterative process using finite element (FE) analysis. In the process, the three elastic constants were adjusted successively until experimental and analytical natural frequencies and related mode shapes ($f_{1,1}$, $f_{2,0}$, $f_{0,2}$) matched. A FE model of the test setup used was developed. The panel was modelled as a shell element, the FFFF BCs were achieved by two supports at the locations of the springs. The supports allow movement in direction 2 (minor axis) and 3 (out-of-plane) but restrain the in-plane movement in direction 1. The FE model for a single-layer panel can be seen in Figure 3.

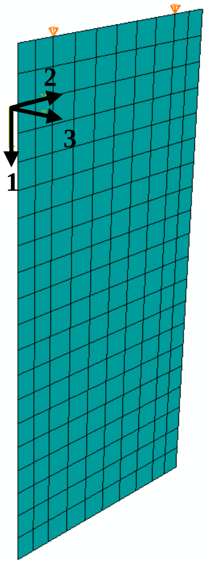


Figure 3: *Finite element model for test setup in FFFF BCs*

In the iterative process within the FE analysis the material properties E_{11}, E_{22}, G_{12} and G_{13} were adjusted until the experimental and analytical natural frequencies and related mode shapes matched. The material properties G_{12} and G_{13}, and ν_{12} and ν_{13} were assumed to be equal. For the density of the panel the values determined during the laboratory tests were used for the corresponding panel. For the material properties E_{33}, G_{23}, ν_{12}, ν_{13}, and ν_{23} constant values for all panels were chosen. A sensitivity study has shown that these values, as well as G_{13} show only minor influence on the natural frequencies. Table 1 shows the selected values for the material properties E_{33}, G_{23}, ν_{12}, ν_{13}, and ν_{23}.

Table 1: *Material properties used for iterative FE process*

E_{33} [MPa]	G_{23} [MPa]	ν_{12}	ν_{13}	ν_{23}
500	50	0.48	0.48	0.455

In this series of tests using methods proposed in [4] and [5], a total of 55 single-layer panels and nine 3-layer CLT panels have been tested with the FFFF BCs.

A second series of modal tests was conducted to investigate additional BCs using a subset of 10 panels. In this series modal tests with BCs of two simply supported opposite edges and the other edges free were undertaken. Tests were performed for the two directions separately, with the span parallel to the grain of the single-layer of the outer layer of the CLT panel (SFSF), and with the span perpendicular to the grain of the single-layer or other layer of the CLT panel (FSFS). In both cases the panels were supported on round steel pipes. The panels were clamped on to the supports by additional pipes to assure a constant contact of the supports and the panels during the tests. The span was 595mm in the SFSF test setup and 578 mm in the FSFS test setup, respectively. Based on [6], natural frequencies and mode shapes were determined and the elastic constants E_{11} and E_{22} were evaluated from the two test setups using only the fundamental natural frequencies. G_{12} could not be determined from this approach. The test setup of a SFSF test and a detail of the clamping situation at the supports can be seen in Figure 4. The same ten panels were evaluated further using modal tests with BCs of all four edges simply supported (SSSS). For the SSSS BCs a closed form solution exists. For these BCs the three elastic constants, E_{11}, E_{22} and G_{12}, can be calculated directly from three experimentally determined natural frequencies as stated in [6, 7]. A total of ten single-layer panels were tested using these BCs.

A third series of tests was then conducted. In this series simultaneous measurement of E_{11}, E_{22} and G_{12} based on the Rayleigh solution of SFSF was also conducted by using three sensitive natural frequencies identified from modal testing. The frequency equations were adopted from the approximate expressions proposed by [8]. The elastic constants were obtained by minimizing the differences between measured and calculated frequencies to less than 1.0 % by an iteration algorithm. The same ten single-layer panels and nine 3-layer CLT panels were tested with this method.

The single-layer panels were tested using the modal testing methods by [4-8]. For the modal test using methods [4, 5], the single-layer panels had a length of 1220mm, a width of 588mm and a thickness of 15.4mm. After the completion of these tests each panel was cut in two halves for process reasons. They were then tested using methods [6-7].

Nine 3-layer CLT panels were fabricated from the square single-layer panels. These 3-layer CLT panels were tested using the modal test method by [5]. The 3-layer CLT panels had a length and a width of 570mm and a thickness of 46mm. The 3-layer CLT was modelled as a solid cross-section in the FE analysis. The elastic constants of E_{11}, E_{22}, G_{12}, and G_{13} were adjusted in an iterative process until natural frequencies and related mode shapes ($f_{1,1}$, $f_{2,0}$, $f_{0,2}$) from laboratory tests and FE analysis matched.

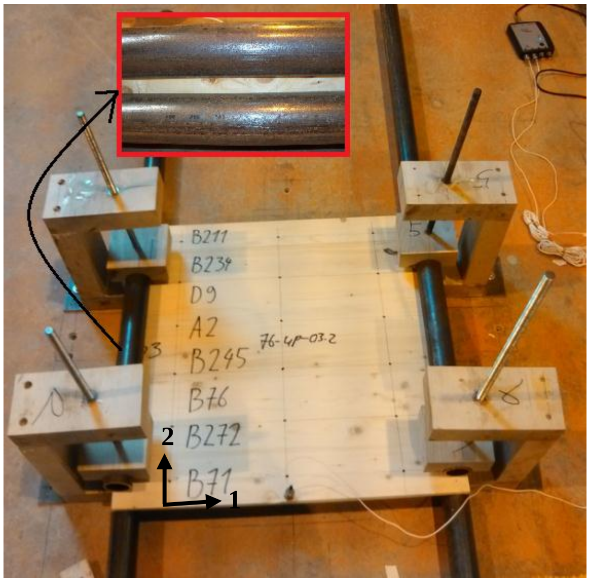


Figure 4: *Test setup and clamping detail for SFSF test*

2.3 STATIC TESTING METHODS

Static tests were performed to evaluate the elastic constants E_{11}, E_{22} and G_{12} of the single-layer panels and E_{11} and E_{22} of the 3-layer CLT panels. The elastic constants E_{11} and E_{22} were evaluated by single-span three-point bending tests based on [9]. In both test setups the specimens were supported over the full width by supports that allowed free rotation. The load was applied at mid-span and distributed 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 edges. The two measurements from the LVDTs were averaged for the calculation of the E values. The E_{11} values were measured using a span of 1100mm and a displacement rate of 8mm/min. After the completion of these tests each single-layer panel was cut into two halves to perform the E_{22} value evaluation. The tests were performed using a span of 500mm and a displacement rate of 0.75mm/min. Figure 5 shows the test setup for the evaluation of the E_{11} values of a single-layer panel.

Figure 5: *Bending test setup for E_{11} value evaluation*

The test procedure for the evaluation of the in-plane shear modulus G_{12} was based on [10]. In the test setup the square panel was supported on two diagonally opposite corners by ball bearings and were loaded on the other two diagonally opposite corners. The span of the supports was 800mm and the distance between the loading points was 800mm. The tests were performed at a displacement rate of 3mm/min. According to [10] 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 to the centre of the panel was determined. The deflections of the quarter points were averaged and used for the determination of the G_{12} values. The test setup for the twisting test can be seen in Figure 6. The elastic properties evaluated in static tests were used as reference values in the comparison of those measured using modal test methods under different BCs.

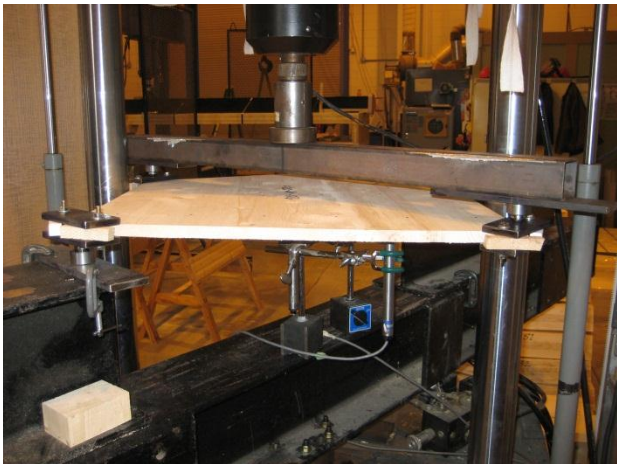


Figure 6: *Twisting test setup for G_{12} value evaluation*

The single-layer plate specimens were tested to determinate their elastic parameters using static tests based on [9, 10]. A total of 55 single-layer panels were tested in static bending. Static twisting tests in accordance to [10] were performed on 18 single-layers to evaluate the in-plane shear modulus G_{12}.

The 3-layer CLT panels were tested using three-point bending tests in accordance to [9]. The specimen size for the modal tests was 570mm (length and width) and 46mm thick. The tests were performed at a span of 500mm and a displacement rate of 0.5mm/min. A total of nine 3-layer CLT panels were tested in static bending. At the time of writing this paper no static twisting tests in accordance to [10] have been performed. Therefore no values for the in-plane shear modulus G_{12} of the 3-layer CLT panels are included in this paper.

3 RESULTS AND DISCUSSION

Single-layer plate modal tests with different BCs, FFFS, FFFF, SFSF, FSFS and SSSS, have been conducted and the elastic properties evaluated. E_{11} and E_{22} of the single-layer panels have been evaluated in static tests as well as G_{12} of some of the single-layer panels. The 3-layer CLT panels have been tested with two BCs of FFFF and SFSF. The E_{11} and E_{22} values of the CLT panels have been evaluated using static bending tests. The modal test methods and its corresponding boundary conditions are listed in Table 2.

Table 2: *Modal test methods and corresponding information*

Modal test methods	Boundary conditions	Elastic constants calculation method	Note
1	FFFS	Closed-form frequency equation [4]	
2	FFFF	FE modelling and iteration [5]	
3	SFSF	Self-developed algorithm based on Rayleigh frequency solution [8]	
4	SFSF&FSFS &SSSS	Three fundamental frequency equations [6]	Three single tests

3.1 SINGLE-LAYER PANEL RESULTS

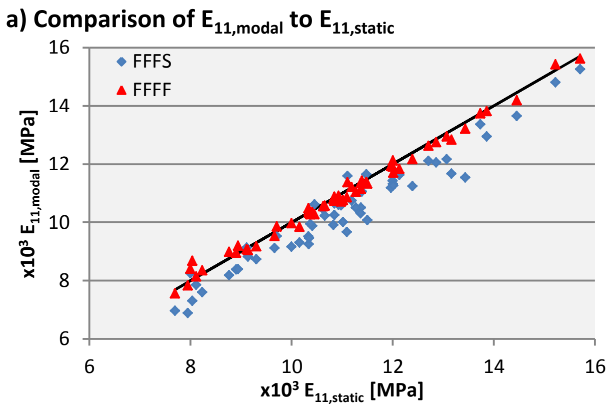
E_{11}, E_{22} and G_{12} of the single-layer panel were evaluated using modal tests with different BCs ($E_{11,modal}$, $E_{22,modal}$, $G_{12,modal}$). The values are compared with the corresponding E_{11}, E_{22} and G_{12} values measured from static tests ($E_{11,static}$, $E_{22,static}$, $G_{12,static}$). Figure 7 shows a comparison of the results measured from static and modal tests. The black lines are the 45 degree lines. Table 3 gives an overview of the maximum, average, and minimum deviation of the modal test values from the static values in percent.

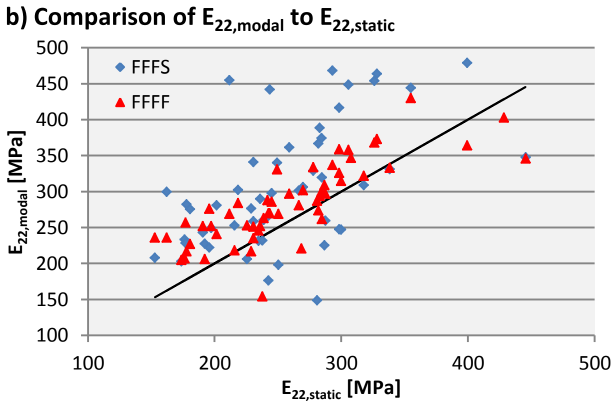
Figure 7 a) shows that E_{11} results from modal tests with both modal test method 1 and 2 (FFFS and FFFF) are in good agreement in general, with the latter giving slightly higher values than the former. It can be seen that the results from modal test method 2 are close to the static test results but the modal test method 1 results are slightly lower than static results. As it can be seen in Table 3 the E_{11} values determined using modal test method 1 lie within a range of -14.1% to +4.5%, the average being -5.7% of the static test values. The average difference of E_{11} values from modal test method 2 is about -0.3%. Only a few samples show a significantly higher difference. The values lie within a range of -3.0% and +8.0% of the static values.

E_{22} values in Figure 7 b) show a much larger deviation than the E_{11} results. In both BCs the modal tests generally lead to an overestimation of E_{22}, but the modal test method

2 results are closer to the static results than the modal test method 1 results. Table 3 shows that the E_{22} values from the modal test method 1 are within the range of -47.1% and +114.9% of the static values with an average difference of about +22.4%. The average difference between the modal E_{22} values from modal test method 2 and static E_{22} is about +11.9%, with a range of -35.2% and +54.5%.

From the G_{12} value graph (Figure 7 c)) and from Table 3 it can be seen that values determined by modal test method 1 show over- and underestimations within a range of -14.4% to +10.9% in this test setup. The modal test method 1 values have an average deviation of about +0.6. The results from modal test method 2 compared to the results from static tests are all underestimated within a range of -20.1% and -0.6%. The average is about -10.9%.


a) Comparison of $E_{11,modal}$ to $E_{11,static}$


b) Comparison of $E_{22,modal}$ to $E_{22,static}$

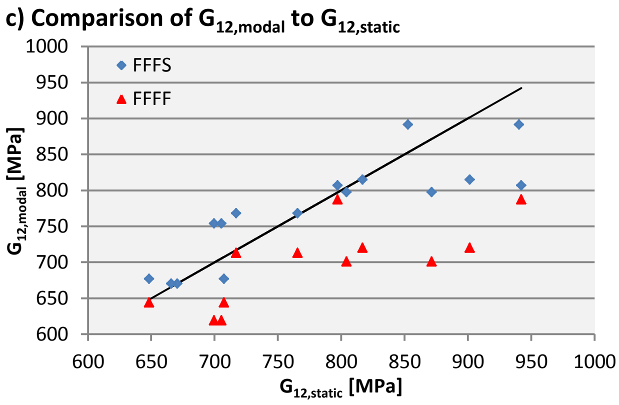

c) Comparison of $G_{12,modal}$ to $G_{12,static}$

Figure 7: *Comparison of single-lay panel properties measured using static tests and modal test method 1 and 2*

Table 3: *Average and extreme values of single-layer panel property deviation results shown in Figure 7*

Property	BCs	Max [%]	Average [%]	Min [%]
E_{11}	FFFS	4.4	-5.7	-14.1
	FFFF	8.0	-0.3	-3.0
E_{22}	FFFS	114.9	22.4	-47.1
	FFFF	54.5	11.9	-35.2
G_{12}	FFFS	10.9	0.6	-14.4
	FFFF	-0.6	-10.9	-20.1

In modal test method 3 (SFSF) and 4 (evaluation based on a combination of SFSF&FSFS&SSSS) a total of ten single-layer specimens were tested. These ten specimens were part of the 55 samples tested in modal test method 1 and 2. For comparison reasons the results from modal test method 1 and 2 of these ten single-layer panels are here presented again. Figure 8 shows the difference of $E_{11,modal}$ and $E_{22,modal}$ values of these ten single-layer panels compared to the corresponding results from static tests. For two of these ten panels comparable data for the G_{12} value exist. The black markers indicate the $E_{11,static}$, $E_{22,static}$ and $G_{12,static}$ values, respectively of the corresponding panel. Table 4 gives the maximum, average and minimum values from the modal tests undertaken with modal test method 1-4. The table shows the relative values for the evaluated E_{11}, E_{22} and G_{12} in percent in comparison with the corresponding static values. Since only two of the specimens that were used in this paper were tested in static twisting tests in accordance to [10] only two data sets are available for comparison. Therefore the maximum and minimum G_{12} values of the data for the different BCs presented in Table 4 are equal to the results from the test specimens.

The E_{11} results (Figure 8 a) and Table 4) show that modal test method 1 based values are underestimated in general. Here the average is -8.0%, the values lie within a range of -9.4% and -4.1%. Modal test method 2 based values show much better correlation with an average difference of +1.0%. The results are within the range -1.6% and +8.0%. Values based on modal test method 3 lie within a range of -13.1% and +5.1% with an average of -3.5%. The values determined by modal test method 4 show an overestimation in all tests within the range of +6.5% - +26.0%, and an average of +13.7%.

The E_{22} results (Figure 8 b) and Table 4) show that modal test method 1 based values are overestimated in general. The range of results is -24.1% and +125.1%. The average is +40.0%. Modal test method 2 based values show only overestimated values within +1.4% and +33.0%, with an average difference of +18.6%. Values based on modal test method 3 are within -23.0% and +18.2% and have an average of -3.7%. The values determined by modal test method 4 show an overestimation in all tests within a range of +50.4% - +96.3%, and an average of +71.7%.

The G_{12} results (Figure 8 c) and Table 4) only contain values from two specimens, nevertheless the graph suggests certain trends. Modal test method 1 based values are overestimated, and the two values are quite close to each other (+9.8% and +10.9%). The modal test method 2 based values are slightly underestimated (-4.4% and -3.4%). Values based on modal test method 3 are overestimated (+5.2% and +11.3%). The values determined by modal test method 4 show an underestimation for both panels (-30.6% and -16.2%). The results from this approach show the highest difference from the static measurements.

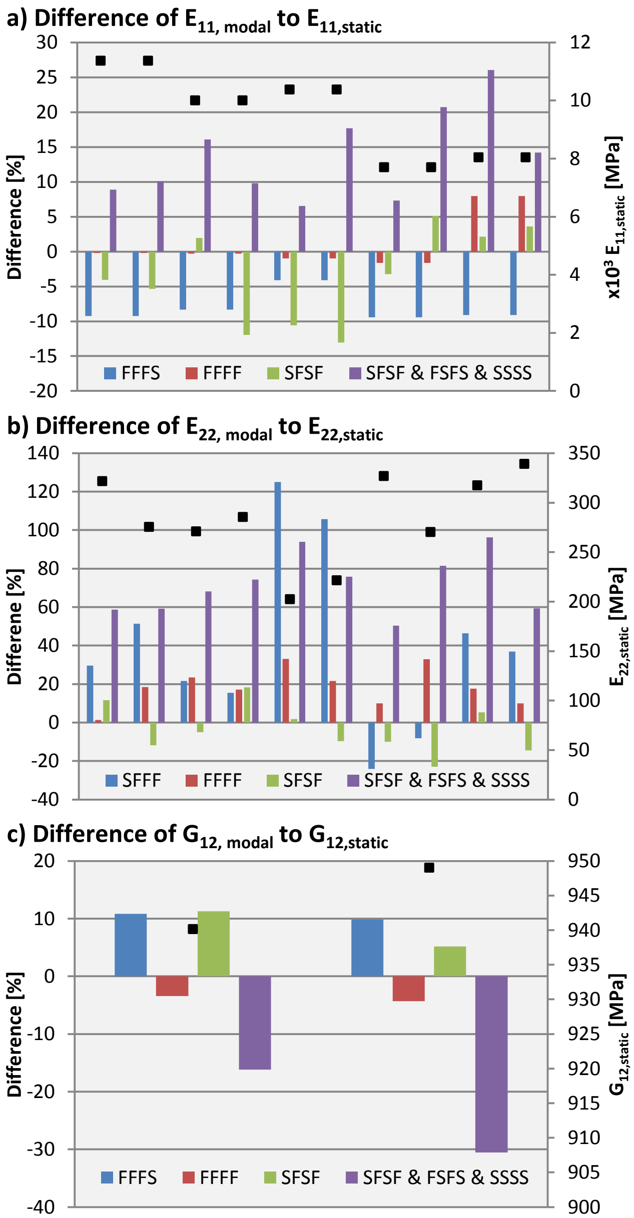


***Figure 8:** Deviation of modal test results for single-layer panels using modal test method 1-4 and static test results*

***Table 4:** Average and extreme values of single-layer panel property deviation results shown in Figure 8*

Property	BCs	Max [%]	Average [%]	Min [%]
E_{11}	FFFS	-4.1	-8.0	-9.4
	FFFF	8.0	1.0	-1.6
	SFSF	5.1	-3.5	-13.1
	SFSF & FSFS & SSSS	26.0	13.7	6.5
E_{22}	FFFS	125.1	40.0	-24.1
	FFFF	33.0	18.6	1.4
	SFSF	18.2	-3.7	-23.0
	SFSF & FSFS & SSSS	96.2	71.7	50.4
G_{12}	FFFS	10.9	10.3	9.8
	FFFF	-3.4	-3.9	-4.3
	SFSF	11.3	8.2	5.2
	SFSF & FSFS & SSSS	-16.2	-23.4	-30.6

3.2 3-LAYER CLT PANEL RESULTS

E_{11} and E_{22} of the 3-layer CLT panels were evaluated from modal tests with different BCs ($E_{11,modal}$, $E_{22,modal}$). The values were compared with the corresponding E_{11} and E_{22} values evaluated from static tests ($E_{11,static}$, $E_{22,static}$).

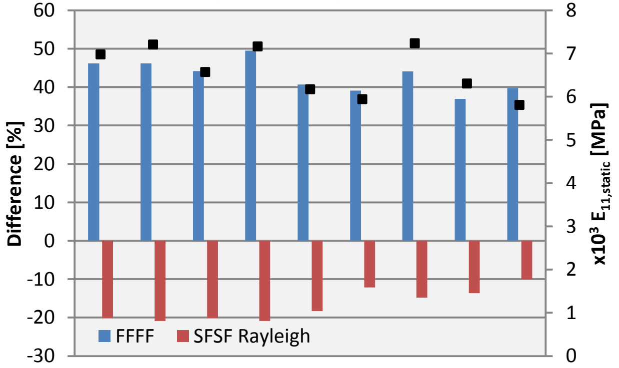
Figure 9 shows the difference of $E_{11,modal}$ and $E_{22,modal}$ values of nine 3-layer CLT panels relative to $E_{11,static}$ and $E_{22,static}$. At the time preparing this paper, no G_{12} values of any 3-layer CLT panel were evaluated in static testing, therefore no G_{12} value comparison is presented. The E_{11} and E_{22} values were measured using modal test method 2 and 3. The results from the SFSF tests were evaluated with a Rayleigh solution. The black markers indicate the $E_{11,static}$ and $E_{22,static}$ values, respectively of the corresponding CLT panel. Table 5 gives the maximum, average and minimum values from the modal tests method 2 and 3. The table shows the values for the evaluated E_{11}, E_{22} and G_{12} values relative to the static results in percent.

It is interesting to note that while the E_{11} values from modal test method 3 are in better agreement with static values than modal test method 2, the opposite is true for the E_{22} results. In the graph showing E_{11} data (Figure 9 a)) and from Table 5, it can be seen that the modal test results from the modal test method 2 show a difference of between +37.0% and +49.5% compared with the static test results, with an average of about +43.0%. The results from the modal test method 3 show a difference between -10.0% and -20.9%, with an average deviation of -16.8%.

For the E_{22} results (Figure 9 b) and Table 5), it can be seen that the results from the modal test method 2 show a difference of between +15.6% and +34.0% from the static test results, with an average of +27.1%. The results from the modal test method 3 show a difference between -28.3% and -50.1%, and an average deviation of -36.3%.

The large difference between the modal and static test results can be explained by the short span in the static tests and the large influence of shear deformation in three-point bending tests with a low span-to-thickness ratio (L/h). The L/h ratio during the static tests was about 10. For CLT panels with L/h ratios of around 10 a shear deformation of about 50% can be expected. The influence of shear deformation has to be evaluated. When accounting for the shear deformation in the bending test, the actual difference between modal and static tests should be considerably less than those shown in Figure 9 and Table 5. Further static tests with proper accounting of shear deformation have been planned to clarify this issue.

a) Difference of $E_{11,\ modal}$ to $E_{11,static}$



b) Difference of $E_{22,\ modal}$ to $E_{22,static}$

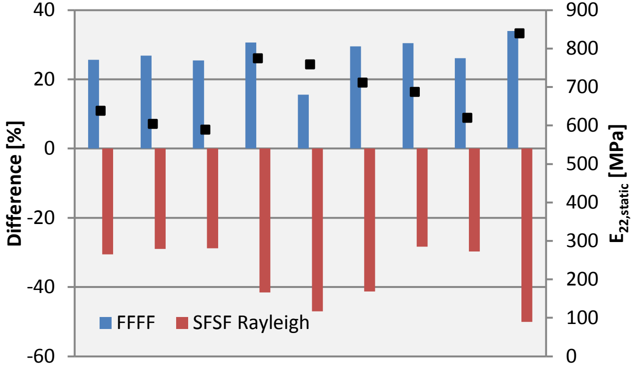


***Figure 9:** Deviation of modal test results for CLT panels using modal test method 2 and 3 and static test results*

***Table 5:** Average and extreme values of single-layer panel property deviation results shown in Figure 9*

Property	BCs	Max [%]	Average [%]	Min [%]
E_{11}	FFFF	49.5	43.0	37.0
	SFSF	-10.0	-16.8	-20.9
E_{22}	FFFF	34.0	27.1	15.6
	SFSF	-28.3	-36.3	-50.1

3.3 INFLUENCE OF BCs ON PROPERTY EVALUATION OF MASSIVE PANELS

Here an overview of the feasibility and the calculation efforts in measuring elastic properties of mass timber panels is presented. Modal test method 1 seems to be feasible for larger panels and do not demand a large area as the test panel is oriented vertically. However, there are concerns related the need to develop a stabilisation setup for the vertically erected panel that will ensure safety during operation while having minimal influence on the measured natural frequencies. The three natural frequencies can be determined in a single test if the range of the desired frequencies is known. The evaluation is based on simple equations, so the calculation effort is small.

Modal test method 2 seems also feasible for larger panels and do not demand a large area. A crane-like setup that provides vertical support and allows mounting and dismounting of the panel, as well as panel fixtures for the suspension are needed. The three necessary natural frequencies can be determined in a single test if the range of the desired frequencies is known. The evaluation is based on a tedious iterative method, but the development of an algorithm could reduce calculation efforts.

Modal test method 3 works well for thin plate based on the Rayleigh frequency solution. This method is feasible for panel products of both small and large dimensions such as full size CLT panels. It has great potential for online testing in the production line. With a well-developed algorithm, the sensitive frequencies can be easily identified from a few frequency spectra up to three. However, for thick panel products, the algorithm should be modified based on thick plate theory considering the effects of shear deformation and rotatory inertia.

Modal test method 4 necessitates three separate tests and setups, which is feasible for small and thin panels. Only three fundamental natural frequencies are needed for simple calculation. Also there is no need to draw mode shapes and identify frequencies. However, the accuracy of this method is not as good as the other BCs, especially for E_{22} and G_{12}. Therefore, this method is only recommended for getting approximate values of a panel.

4 CONCLUSIONS

Modal test method 1 was only used for the evaluation of E_{11}, E_{22} and G_{12} values of single-layer plates. In general these BCs lead to an underestimation of E_{11} values, but overestimations can occur. The results lie within a reasonable range. The results of the E_{22} evaluation show a wide range of over- and underestimations. The G_{12} results show over- and underestimations within a similar range to the one for E_{11}. Modal test method 1 appears to be useful as a rough estimation of E_{11} and G_{12} values. With the selected arrangement, an E_{22} value evaluation with modal test method 1 is not recommended. An evaluation using different natural frequencies might help to increase the precision of the E_{22} evaluation. The test setup seems feasible for bigger panels. The required three natural frequencies can be determined simultaneously if their range is known. The calculation procedure is based on use of simple equations.

Modal test method 2 was used for the evaluation of E_{11}, E_{22} and G_{12} values of the single-layer panels and for the 3-layer CLT panels. In general these BCs lead to an underestimation of E_{11} values, but overestimations can occur. The results are within a fairly close range. The results of the E_{22} evaluation show a wide range and tend to be overestimated. In general the G_{12} value related results show underestimations of up to -20%. Modal test method 2 appears to be useful for the evaluation of E_{11} values and rough estimation of G_{12} values. The range for E_{22} values is closer than for modal test method 1, but still fairly wide. An evaluation using different natural frequencies might help to increase the precision of the E_{22} and G_{12} evaluation. The test setup seems feasible for bigger panels. The required three natural frequencies can be determined simultaneously if their range is known. The evaluation is based on a tedious iterative method, but an algorithm could lead to a lower calculation efforts.

Modal test method 3 was used for the evaluation of E_{11}, E_{22} and G_{12} values of the single-layer panels as well as for the small size 3-layer CLT. With the algorithm developed by the authors, the accuracy for single-layer panels is fairly good. But for small size CLT in this study, due to its width/ thickness ratio, the accuracy is not as good as modal test method 2. In the authors' other tests not reported herein, this method worked well for full size CLT panels. More attentions will be paid to small size CLT panels which should be considered as thick plates.

Modal test method 4 was used for the evaluation of E_{11}, E_{22} and G_{12} values of single-layer plates. In general, it leads to overestimations of all three values to different extent. The method is only feasible for approximate evaluation of elastic constants.

5 FURTHER RESEARCH

- Further modal and static tests on 3- and 5-layer CLT panels will be undertaken in order to evaluate the applicability of different BCs for the evaluation of the elastic properties of CLT panels.
- Further bending tests are needed to obtain the true E_{11} values of the CLT panels and to determine the influence of shear deformation on the obtained results.
- Static tests for the evaluation of G_{12} values will be undertaken in order to compare the applicability of the different BCs.
- Modal test method 3 shows great potential for online testing, especially for massive time panel products. Future research will focus on accuracy improvement and frequency identification. Thick plate theory will be adapted for thick panel products to improve its feasibility and to measure transvers shear modulus as well.

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