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CHARACTERIZING INFLUENCE OF LAMINATE CHARACTERISTICS ON ELASTIC PROPERTIES OF SINGLE LAYER IN CROSS LAMINATED TIMBER

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ABSTRACT: Cross laminated timber (CLT) has potential for load transfer in two directions when loaded in out of plane direction. In order to make effective use of this potential it is necessary to evaluate layer properties and their effects on the final product performance. This paper presents the approach and outcomes of an on-going study dealing with the evaluation of material and structural characteristics of components and their effects on overall CLT properties using modal testing. Laminate characteristics were first determined and “homogenized” single-layer plates were edge-glued. Single-layer panel characteristics were determined by modal tests. Measured natural frequencies and mode shapes were compared with finite element results. Relationships between laminate properties, like width and growth ring orientation, and single-layer elastic properties, like elastic and shear modulus, were found.

KEYWORDS: Cross laminated timber, Modal testing, Two-way bending, Elastic properties, Laminate aspect ratio

1 INTRODUCTION

In order to compete against other building materials, like steel and concrete, it is necessary for the timber industry to develop new engineered wood products. Cross laminated timber (CLT) is one of these new products. As a result of the alternating grain direction of the adjacent layers, CLT shows not only material dependent anisotropy, but also structural anisotropic behaviour. Due to their lay-up, CLT panels show potential for two-way resistance action and therefore an economical use in floor construction. Current design procedures for CLT under out-of-plane loading however are based on one-dimensional beam models. This does not utilize the full potential of CLT panels. Two-way plate models based on advanced laminated plate theory have been developed to predict normal and shear stress distributions, as well as deflection and natural frequencies of CLT panels under transverse loading. These models have the potential to be adopted for design use. However, a major challenge for using these advanced laminated plate models is the determination of appropriate input properties for individual layers, especially in the direction transverse to the grain of the laminates. This is because each layer is not a continuous plate. Rather, it is formed by connecting laminates edge-to-edge to form the layer. Influence of edge-gluing characteristics, width to thickness ratio of laminates (aspect ratio), and layer thickness will affect input properties. The objective of this on-going study is to develop relationships between laminate properties and layer elastic properties for input into two-way plate models. This paper presents some preliminary results of the study.

2 METHODOLOGY

2.1 MATERIAL AND GEOMETRICAL ASPECTS

Wooden boards, mainly spruce with various growth ring patterns were randomly selected and conditioned to a moisture content of about 13%. In order to maintain the achieved moisture content during further processing stages, the material is stored in a conditioning chamber with a constant climate. To facilitate further processing, all boards were sized to constant dimensions after the conditioning process has been completed, The boards were cut to a length of 1500mm, a width of 128mm and were planed to a thickness of 19mm.

2.2 EVALUATION OF LAMINATE CHARACTERISTICS

The modulus of elasticity (E) of the 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 properties of the boards, the first and second natural frequencies in free-free support conditions were determined. Based on their natural frequencies, the board dimensions and density, the elastic modulus and the

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shear modulus were calculated. 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. The boards were separated into three groups based on growth ring orientation: flat-sawn, quarter-sawn and boards with a growth ring orientation of about 45°. After grouping, the laminates were cut from the boards. In order to investigate the influence of laminate width on layer characteristics, three laminate widths were included: 120mm, 76mm and 32mm. The three laminate widths led to three laminate aspect ratios of approximately 2:1, 5:1 and 8:1. Boards with major defects were either excluded, exchanged or ripped to a smaller laminate width in order to allow removal of the defects or to distribute the defects over the final layer.

The laminates within each group were edge-glued by use of a 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 changes in the moisture content the alternating pith location of adjacent laminates leads to less surface distortion and cupping of the single-layer panel and therefore better dimensional stability. After glue application, a layer of laminates was clamped in a mechanical multi-jack press. The pressure of each jack can be controlled by an adjustable maximum torsional moment which is applied to threaded rods. The laminates were held down and aligned by moveable pneumatic dies while the pressure for the edge-gluing was applied. The layer gluing process was undertaken in two steps in order to prevent buckling and pop out of the laminates during edge clamping. First, two layers, half the final layer width, were edge-glued and then these two layers were edge-glued together to the final full width.

The selected characteristics for the grouping of the laminates, namely the 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 "homogenized" layers with similar laminate characteristics. After the gluing process the layers were re-sized to uniform dimensions. First they were sanded to a thickness of about 15.4mm, then cut to a width of 588mm and a length of 1220mm. In total 55 single-layers were produced, 27 representative single-layer panels were tested in this first step of the investigation. The group of selected single-layer panels included panels with 9 combinations of aspect ratio (3) and growth ring orientation (3).

2.4 EVALUATION OF LAYER CHARACTERISTICS

The 27 selected single-layer plate specimens were tested to determine their elastic parameters using modal tests developed by Sobue and Katoh [3] and Gsell et al [4]. The 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 simultaneously by the determination of three natural frequencies. 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 condition was 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 values of the elastic properties and specimen geometry. The natural frequencies used in the calculation were selected based on a sensitivity study.

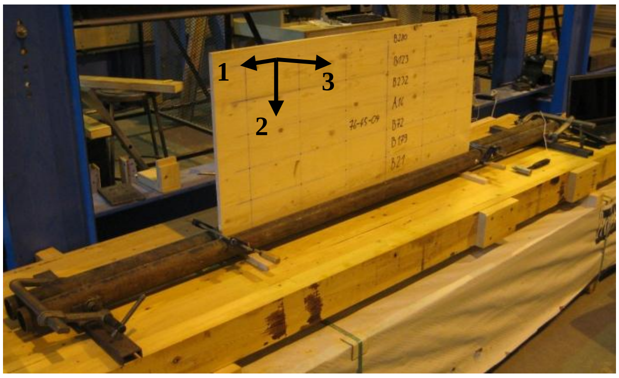

Figure 1: *Test setup for modal tests by [3]*

In an attempt to evaluate the validity of the test method [3], a finite element (FE) modelling exercise was also conducted. The elastic properties measured using method proposed by [3] were used as input for a FE model as material properties. The FE model was designed to replicate the test setup of [3]. The single-layer panel was modelled as a shell element. The boundary condition of the test setup was simulated as a pinned support in the FE model. As shown in Figure 2, two single pinned supports are located at the vertical supports in the test setup, and a series of pinned support points along the supported edge are used to model the steel pipe support in the test setup The natural frequencies of single-layer panels determined by laboratory tests were compared with natural frequencies calculated by a FE model.

The method described in [4] was first developed for the determination of elastic properties of CLT panels, although as for method [3] it is equally applicable to any orthotropic plate. In theory all nine elastic constants for orthotropic plate can be calculated using this approach.

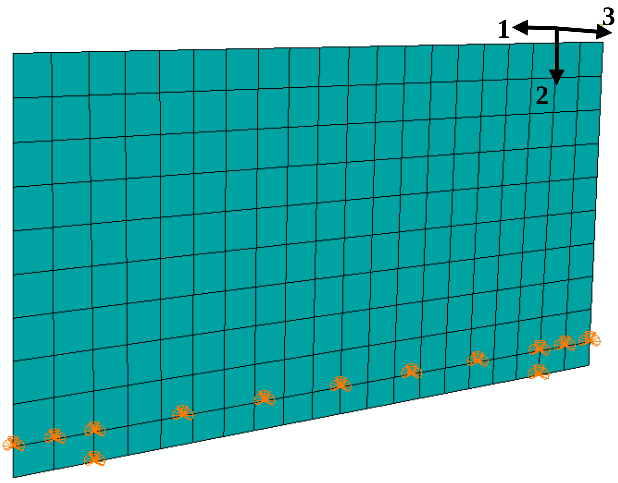

Figure 2: *Finite element model for test setup by [3]*

However for CLT panels, the interested properties are the elastic moduli E_{11} and E_{22} and the shear moduli G_{23}, G_{13} and G_{12}. The method is based on iterative calculation within an advanced plate theory model until the calculated natural frequencies and mode shapes match with the measurements from laboratory tests. Laboratory tests and plate theory model are based on free-free boundary conditions achieved by suspending the panels with strings in a vertical position. The physical test setup can be seen in Figure 3. At this stage of the current research project only the measurement of the natural frequencies and the related mode shapes of the single-layer panel was completed. The calculation of elastic properties using advanced plate model is yet to be performed.

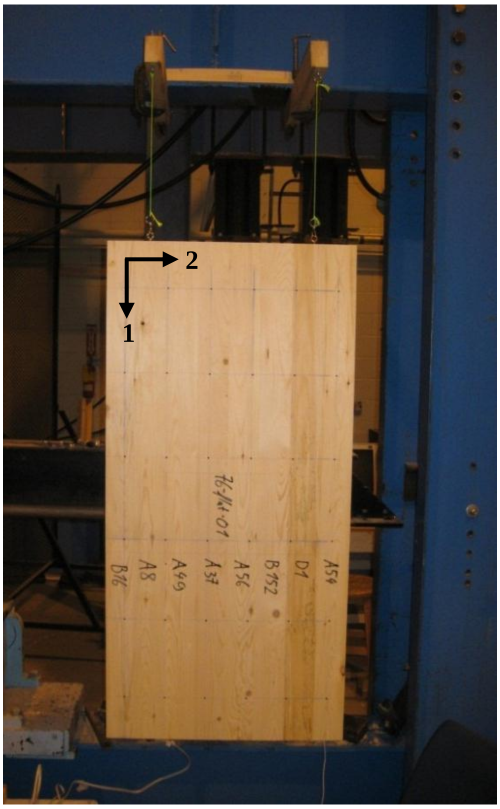

Figure 3: *Test setup for modal tests by [4]*

As for the case of the Sobue and Katoh method [3] a FE model of the test setup was developed. The single-layer panel is modelled as a shell element, the free-free boundary conditions were achieved by two roller supports at the locations of the srings. The roller 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 4. The measured natural frequencies and mode shapes were then compared with FE model predicted values based on material properties estimated using the method by [3] previously.

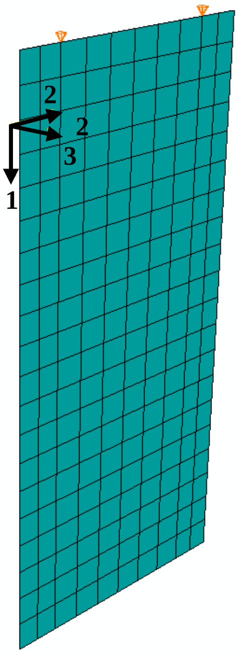

Figure 4: *Finite element model for test setup by [4]*

The two modal test setups were used in order to compare and verify the results for the single-layer elastic properties gained by the use of the method by [3]. The two setups were selected since their basic approach and their boundary conditions differed.

To evaluate the influence of aspect ratio and growth ring orientation on the overall characteristics of single-layers, E_{11} and G_{12}, are generally presented in this paper relative to the corresponding average elastic and shear modulus of all the laminates used in forming the “homogenized” layer, $E_{average}$ and $G_{average}$.

3 RESULTS AND DISCUSSION

A comparison of natural frequencies and mode shapes of the laboratory tests with ones calculated by FE models, using the characteristic properties determined by the method proposed by [3], shows good correlation in general.

For the test setup with a simple support along one edge and free boundary conditions for the other edges [3], the three selected frequencies and mode shapes were compared with the ones from the related FE model. The deviation of the FE model based results to the laboratory results is less than 2% for frequency $f_{3,1}$, which is mainly driven by E_{11}. The other frequencies $f_{1,1}$ and $f_{1,2}$, which are dominate by G_{12} and E_{22}, show a maximum deviation of about 11%. For the free-free condition test setup based on [4] 14 frequencies and their corresponding mode shapes were calculated for each layer using the FE model. At least 10, generally 12 modes and their frequencies were identified from the laboratory tests of each specimen. The reasons for the difficulties in identifying all 14 modes are the closeness of adjacent modes in the spectrum, and the inevitable selection of an impact or response point that is close to the node of the mode shape of some of the modes. This raises the question of applying the test method to estimating CLT elastic properties. Nevertheless frequencies and mode shapes related to E_{11} and G_{12} show good correlation between laboratory test and FE model results. The deviation for E_{11} related frequencies is less than 6%, while G_{12} related frequencies show a maximum deviation of less than 10%. Only E_{22} related frequencies show higher deviations.

Figure 5 shows the relationships between the laminate width and the increase of E_{11} relative to $E_{average}$, and G_{12} relative to $G_{average}$ respectively. The trend lines are also shown. Figure 6 shows the relationships between the laminate growth ring orientation and the increase of E_{11} to relative to $E_{average}$, and G_{12} relative to $G_{average}$ respectively, and the trend lines.

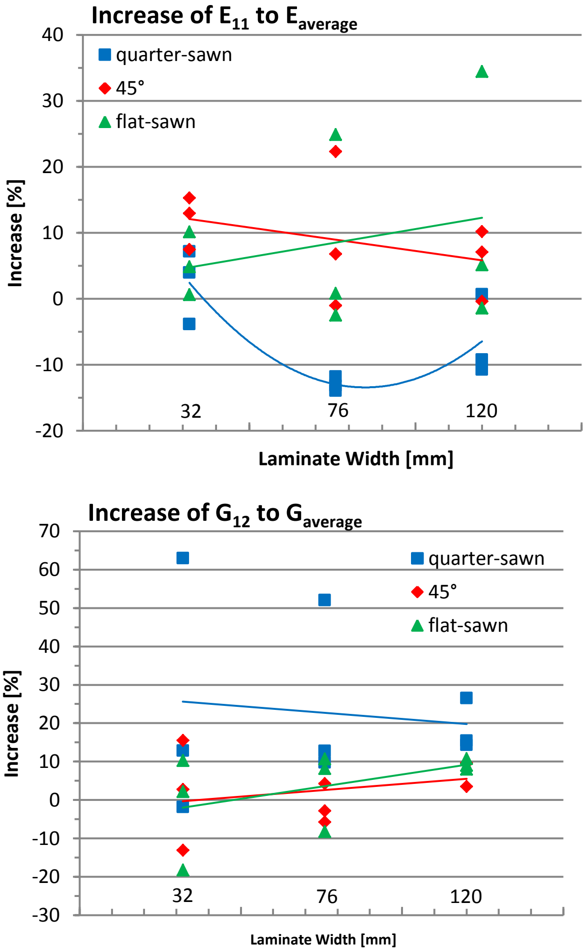

Figure 5: *Influence of laminate width on elastic properties E_{11} & G_{12}*

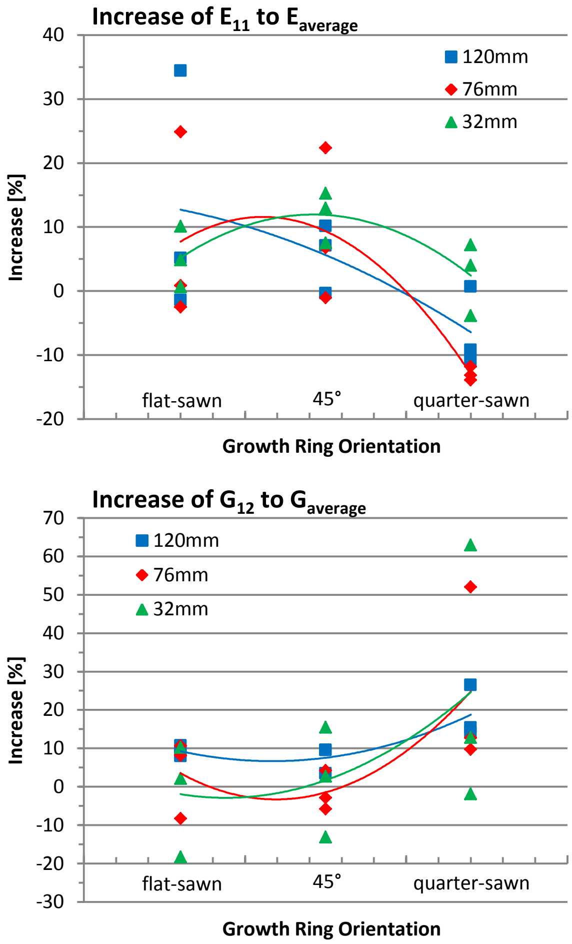

Figure 6: *Influence of growth ring orientation on elastic properties E_{11} & G_{12}*

Although at first glance of Figure 5 and Figure 6, there is no clear trend regarding the influence of either laminate aspect ratio or growth ring orientation on elastic properties of single plate, some specific relationships between these elastic properties and laminate characteristics can be observed. Figure 7 shows selected E_{11} results. It can be seen that almost all layers with a laminate width of 32mm show an increase in E_{11} in relation to $E_{average}$. This could be explained by the stiffening effects caused by the extra glue lines in the plate with narrow laminates. A similar influence can be observed for layers with a growth ring orientation of about 45° irrespective of laminate width. The reason for this is unknown. On the contrary it appears that layers made from quarter-sawn laminates tend to show a reduction in E_{11} in relation to $E_{average}$, except for the narrowest laminates. This would mean that there may be counter-acting effects of laminate width and growth ring orientation. All other laminate parameter combinations show less pronounced effects E_{11}.

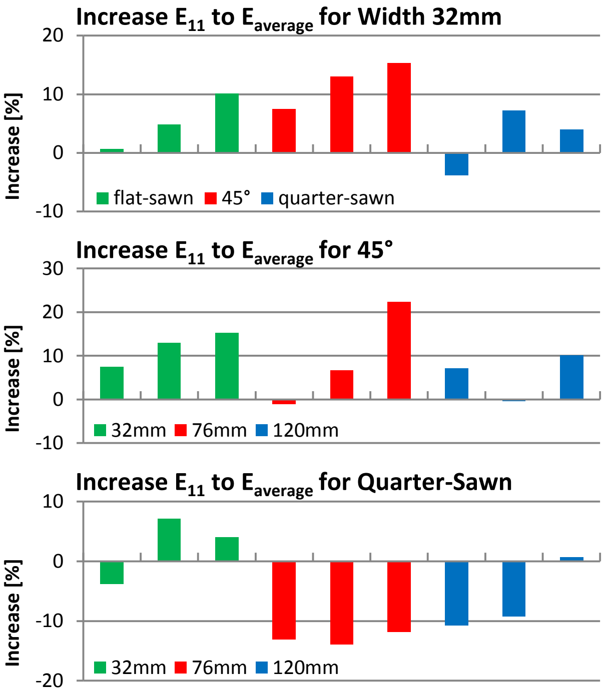

Figure 7: *Influence of laminate characteristics on E_{11}*

Figure 8 shows selected results for G_{12}. It can be seen that all layers made by laminates with a width of 120mm show an increase in G_{12} in relation to $G_{average}$. Layers produced from quarter-sawn laminates also show consistent increase in G_{12} relative to $G_{average}$. This also applies to most of the single-layers made with flat-sawn laminates. All other combinations of investigated characteristics show less obvious trend on G_{12} in relation to $G_{average}$. These results may indicate that wider laminates and quarter sawn laminates could be beneficial in enhancing G_{12} of CLT.

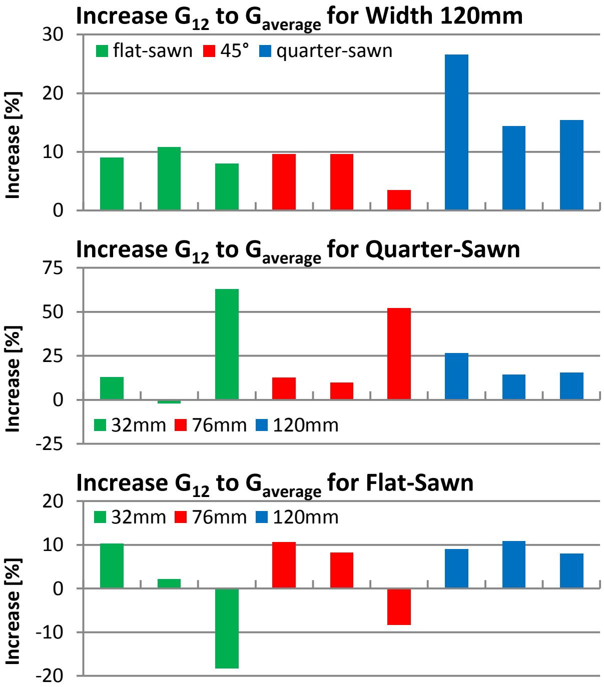

Figure 8: *Influence of laminate characteristics on G_{12}*

4 CONCLUSIONS

The small differences between measured frequencies and FE model predictions for the two test methods lead to the conclusion that property values for E_{11} and G_{12} of single-layer panels can be reliably estimated using modal testing method proposed by [3]. Further work is required to evaluate method proposed in [4].

From the comparison of the evaluated layer properties (E_{11} and G_{12}) with averaged laminated properties ($E_{average}$ and $G_{average}$) for various combinations of laminate aspect ratio and growth ring orientation the following conclusions can be drawn:

- A smaller laminate width or aspect ratio lead to an increase in E_{11} compared to $E_{average}$
- A growth ring orientation of about 45° leads to an increase in E_{11} compared to $E_{average}$
- A quarter-sawn growth ring orientation leads to a reduction in E_{11} compared to $E_{average}$
- Wider laminates or large aspect ratio lead to an increase in G_{12} compared to $G_{average}$
- A quarter-sawn growth ring orientation leads to an increase in G_{12} compared to $G_{average}$

The authors are aware that the amount of test samples is rather small at this point. The findings will be monitored during the analysis of the remaining single-layer panels and future research.

5 FURTHER RESEARCH

After the single-layer panel modal tests have been completed and analysed, selected single-layer panels will be tested in static tests to verify the results from the modal testing analysis. Static test will be conducted with different boundary (one- and two-way bending) conditions. The results from modal and static tests will be analysed with respect to the laminate grouping characteristics, elastic modulus (E), shear modulus (G) and laminate growth ring orientation. Their influence on the layer characteristics will be evaluated. It is expected that relationships between the different grouping characteristics and the single-layer properties can be derived.

After the single-layer panels have been analysed, scaled CLT panels will be formed by face gluing single-layer panels together. The formed CLT panels will be tested using modal testing methods [3,4] and static tests in order to evaluate their overall elastic properties and the influence of layer properties on CLT panel properties. Starting with 3-layer CLT panels the number of layers will be increased successively after modal and static test have been completed. In order to gain information about internal interlayer behaviour strain gauges will be employed within the interlayer sections at selected locations in some panels. Through this approach the relationship between laminate properties and characteristics on elastic properties of an edge-glued layer will be established. These layer properties will be used as input into an advanced laminate plate analytical model and finite element model to generate predicted responses (deflection and stress distribution) caused by out-of-plane loading, and natural frequencies under the same boundary conditions as the modal tests. These predicted responses will be compared with measured responses from the static CLT plate tests to evaluate the validity of the advanced laminate plate model.

In addition to edge-glued CLT panels, CLT panels without edge-gluing will also be fabricated using the laminates from the same source. These CLT panels will be also tested in modal and static tests, and the results will be compared with those of edge-glued CLT panels. This would allow the influence of edge-gluing of laminates on CLT panel properties to be evaluated.

In order to gain more information about the applicability of the derived relationships on full scale CLT panels it is planned to carry out modal and static tests on full scaled CLT panels using a similar approach as for the scaled specimens. Samples of laminates will be obtained from the production line of an industry partner and tested to obtain model input properties. Full scale CLT panels will be produced and tested using modal testing method to evaluate their overall properties and to evaluate the validity of the derived relationships for full scale CLT panels.

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