Diaphragm shear and diagonal compression testing of cross-laminated timber

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Abstract

To learn the characteristics of a cross-laminated timber (CLT) panel, it is crucial to perform experimental tests. This study presents two experimental test methods to measure the in-plane shear modulus of CLT panels. This characteristic can be measured by multiple methods such as the picture frame test, the diagonal compression test, and the diaphragm shear test. In this study, the same CLT panels are tested and evaluated in the diaphragm shear test and the diagonal compression test to see if more reliable results can be achieved from the diaphragm shear test. This evaluation is done by experimental tests and finite element simulations. The theoretical pure shear simulation is used as a reference case. Finite element simulations are made for both edge glued and non-edge glued CLT panels. Nine CLT panels are tested in the diaphragm shear test and the diagonal compression test. During ideal conditions (uniform material properties and contact conditions), all three simulated methods result in an almost equal shear modulus. During the experimental testing, the diagonal compression test gives more coherent results with the expected shear modulus based on finite element simulations. Based on the diaphragm shear test results, the CLT panels behave like edge glued, but this situation is dismissed. However, during ideal conditions, the diaphragm shear test is seen as a more reliable method due to the higher proportion of shear in the measured area.

Article Highlights

- Comparing the two experimental methods: the diaphragm shear test and the diagonal compression test.
- Using the theoretical pure shear simulations to verify the experimental methods.
- Experimental testing and finite element analysis of the same cross-laminated timber panel.

Keywords Cross-laminated timber · CLT · Diagonal compression test · Diaphragm shear test · In-plane shear modulus

1 Introduction

To be able to learn more about cross-laminated timber (CLT), testing is crucial. CLT is a panel consisting of cross-wise arranged layers of wooden boards. These wooden boards can be either edge glued or non-edge glued. A

CLT panel is commonly constructed in three, five, seven or nine layers. Due to the dimensional stability, the layout of the layers is usually symmetrical [1]. The fibre direction of the boards is denoted as the main laminate direction of the layer. Based on the characteristics and dimensions of the boards, different properties of the CLT panel can

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be achieved [2, 3]. One of these properties is the in-plane shear modulus (CLT seen as a material), G , or also called the in-plane shear stiffness (CLT seen as a component). The derivation of correct design parameters of CLT panels is an important issue [4]. According to European Assessment Document (EAD) 130,005-00-0304 [5], G should be calculated based on a four-point flexural test described in the European standard EN 408 [6]. This testing procedure does not only shear the CLT panel, but also mainly bends it. Some methods, such as the picture frame test [7], the diagonal compression test [8], and the diaphragm shear test [9], are trying to mainly shear the CLT panel. These methods will give the possibility for the test sample to have a failure mode of shear instead of bending [9, 10].

The picture frame test is a biaxial method where a square CLT panel is compressed in one diagonal and simultaneously stretched in the other diagonal. Please refer to Bosl [11] and Björnfor et al. [12] for more details on the test procedure. Other methods, similar to the picture frame test, have been performed by Traetta et al. [13] and Bogensperger et al. [14]. The diagonal compression test and the diaphragm shear test are a uniaxial method. These two methods will be analysed in this work. The diaphragm shear test, the diagonal compression test and the picture frame test have been reported to give acceptable results [7–9]. A comparison has been previously performed between the picture frame test and the diagonal compression test methods [7]. In the study by Turesson et al. [7], the same CLT panels were tested in both the picture frame test and the diagonal compression test and the results were compared. The study concluded that the picture frame test gave more reliable results due to the unknown distribution of the in-plane shear stress during diagonal compression. For the picture frame test, the used equation was also empirically derived. The diaphragm shear test, created by Brandner et al. [9] and based on Kreuzinger et al. [15], has been used to measure G for CLT panels. In the diaphragm shear test, a CLT panel is tested in a similar way as a standard load carrying compression test, i.e., in in-plane compression by the longest direction of the CLT panel. One difference is the arrangement of the boards in the CLT panel. In the diaphragm shear test, the CLT panel is cut at an angle of 45° from a larger CLT panel. By compressing this CLT panel, no wood fibres will be parallel or perpendicular to the loading direction. This compression will become like the diagonal compression of a standard square CLT panel. A difference between the diagonal compression test and the diaphragm shear test is that the load during diaphragm shear test is added further away from the measured zone (central region). This has the benefit of reducing the effects from the supports and increasing the possibility of achieving a pure shear state in the central region. Another difference between the diaphragm shear

test and the diagonal compression test is that the supports in the diaphragm shear test neither restricts nor forces the CLT panel to perpendicular-to-force deformations.

In the study by Brandner et al. [9], three different equations were used to calculate the G value. None of these equations gave an equal result. The authors preferred the equation based on the European standard EN 408 [6] due to its more stable outcome and the independency of pre-defined material properties.

Both the picture frame test and the diagonal compression test methods have been analysed by finite element (FE) simulations; please refer to Turesson et al. [8, 16] for more details about these methods. The diaphragm shear test procedure was evaluated as a reliable method by Brandner et al. [9], but it is unknown if a CLT panel tested in the diaphragm shear test would result in a more reliable G compared to the diagonal compression test or the picture frame test.

The diagonal compression test has been well studied in several publications [7, 8, 10, 17, 18] and provided acceptable G values. However, there is no study comparing the diaphragm shear test with the diagonal compression test. This study will make a comparison between the diagonal compression test and the diaphragm shear test by experimental testing and FE simulation. This will make it possible to demonstrate if the diaphragm shear test is a more reliable method to measure G than the diagonal compression test.

Henceforth, the manuscript organization is as follows. First is a presentation of one theoretical and two experimental test methods analysed by finite element (FE). Thereafter, the two experimental methods are explained in practical usage. Following, in the results and discussion, the three methods are compared based on FE results and experimental measurements. Finally, the conclusions are presented.

2 Method

2.1 FE-analysis

Three different methods (see Fig. 1) were simulated by the commercial FE software Abaqus [19]. By using FE simulations, it was possible to obtain a theoretical shear modulus based on the respective test methods. The diaphragm shear simulation was performed based on the testing procedure used by Brandner et al. [9]. The diagonal compression simulation was performed based on Dujic et al. [17] and Andreolli et al. [10]. The pure shear simulation was based on Turesson et al. [7]. All three methods are shown in Fig. 1a–c.

Fig. 1 Diaphragm shear simulation **a**, diagonal compression simulation **b**, and pure shear simulation **c**. The measured zone is illustrated by the transducers in the centre of the diaphragm shear simulation and diagonal compression simulation models. The arrows in **a** show the main laminate directions of the odd (solid line) and even (dashed line) layers. The dash-dotted line illustrated in the CLT panel **a** shows the simulated area in diagonal compression simulations and pure shear simulations [mm]

The models were constructed by adding multiple boards to represent a single 5-layer CLT panel. The boards had a dimension of 180×30 mm and 158×20 mm (width $\times$ thickness) in the odd and even numbered layers, respectively. No gaps were used between the adjacent boards. All boards were constructed as single parts without consideration of lengthwise joints. The initial model was the diaphragm shear simulation. From this simulation, the core of the CLT panel was cut and simulated in diagonal compression simulation and pure shear simulation, as shown by the arrow from Fig. 1a, b and c. By this method, the board arrangement of the CLT panel was identical throughout the test simulations. A symmetry plane in the z-direction (thickness direction) was used for all models. Hence, only half of the CLT panels were modelled which resulted in a lower calculation time.

To see the range of G , both edge glued and non-edge glued models were simulated for all three methods. Contact conditions were applied only on the glued surfaces. In real CLT panels, small gaps can exist between the side edges, and therefore, no contact condition was applied between the side edges of the boards in the non-edge glued models. By not considering the normal direction contact between the side edges, the worst case is assumed. This assumption may not be suitable in case of out-of-plane bending. The same contact conditions were used on the glued flat sides (layer-to-layer) and between the glued side edges of the boards. The contact condition was created by restricting separation/penetration and slip between the glued surfaces. Material data used in the analysed models were obtained as mean values from SS-EN 338:2016 [20] and calculated to three unitless material ratios. The radial, E_r , and tangential, E_t , moduli of elasticity

were 0.0336 of the longitudinal modulus of elasticity, E_l . The shear moduli G_{lr} and G_{lt} were 0.0627 of E_l , and the rolling shear modulus, G_{rt} , was 0.10 of G_{lr} [21]. Due to small influence, all three Poisson's ratios were set to zero according to Turesson et al. [3] and Berg et al. [18]. No material variation was used. For all models, an approximately global element size of 10 mm and C3D20R brick elements were used.

The CLT panel simulated in diaphragm shear simulation had a height, L_d , of 1500 mm, a width, b , of 500 mm and a thickness, t , of 130 mm. The size of the CLT panel and the measured zone was chosen according to Brandner et al. [9] and Silly [22]. A compressing force, F_d , of total 300 kN was used as shown in Fig. 1a. As a boundary condition, the bottom of the CLT panel was restricted from movements in the y-direction by setting the nodal displacements to zero. To simulate a friction free surface between the support and the CLT panel, no restriction was used in the x-direction. A deformation picture was made by creating a set only containing the elements used in the diagonal compression test and pure shear method simulations, as shown in Fig. 1a. To remove the global movements, the displacements were adjusted, and the zero position was set at the lowest point of the diamond-shaped central region. By this method, the deformations in the central region become comparable with the diagonal compression test and pure shear method simulations.

In the diagonal compression simulation, the core of the CLT panel (353×353 mm) was compressed as shown in Fig. 1b by a force of 100 kN. The bottom support was fixed from movements in both the x- and y-direction. In the contact between the supports and the CLT panel, the previously described contact condition was used. No

deformation was assumed in the supports; therefore, the supports were created by rigid elements. This made the FE simulation faster. By using the previously described contact condition, the CLT panel became fixed to the two supports and the local deformations close to the supports became restricted. This small effect was neglected when the results were measured.

For the pure shear method simulation, a surface traction force, F_p , of 6.5 N/mm (length) was used on all four side edges of the CLT panel, see Fig. 1c. The corner numbered one was fixed from the movements in both the x- and y-direction and the corner numbered four was fixed from the movements in the x-direction. The resulting displacement, d_y , was measured at the corner numbered three.

The deformation of the CLT panel was measured as shown in Fig. 1a–c. In the case of diaphragm shear simulation and diagonal compression simulation, the deformation was measured locally in the central part of the CLT panel. A sketch of the measuring zone is shown in Fig. 2 where the initial positions of the measuring points are illustrated with x-marks. The short names for the analysed methods were d , dc and p for the diaphragm shear simulation, diagonal compression simulation, and pure shear simulation, respectively. The initial measuring length, $L_{M,i}$, was the length between the measuring points before loading. The index i was set to d or dc depending on the analysed model. In this study, $L_{M,d}$ and $L_{M,dc}$ were set to 400 and 200 mm, respectively. The size of the measuring zone was not equal due to the expected impact from the supports during the diagonal compression test; see Turesson et al. [8] for more information. The displacements were measured both parallel (active) and perpendicular (passive) to the compressing force direction, as shown in Fig. 1a, b. The resulting displacements, $\Delta d_{active,i}$ and $\Delta d_{passive,i}$, were measured for the load increment, ΔF_i .

Fig. 2 Measuring zone as shown in Fig. 1a, b after deformation for the diaphragm shear simulation and diagonal compression simulation. The x-marks illustrate the position of the measuring points before deformation

The shear modulus, G_i , was calculated using Eq. (1). Because of the nonuniform shear stress distribution, the adjustment factor, α_i , was set equal to 1.0 and 2.52 for i equal to d and dc , respectively [8, 9]. The equation used to calculate G_d was created by Brandner et al. [9]. The equation used to calculate G_{dc} was created by Turesson et al. [8], which was based on the G_d equation by Brandner et al. [9]. Both equations were based on SS-EN 408 [6].

$$G_i = \alpha_i \times \frac{L_{M,i}}{tb} \times \frac{\Delta F_i}{2(|\Delta d_{active,i}| + |\Delta d_{passive,i}|)}, \quad i = d \text{ or } dc \quad (1)$$

In the case of the pure shear method, the G_p was calculated according to Eq. (2). For more information please refer to Turesson et al. [3].

$$G_p = \frac{F_p}{td_y} \quad (2)$$

A material independent shear modulus ratio, G_i^* , was calculated for each simulated test method, see Eq. (3). This equation made it possible to compare the result independent of material data.

$$G_i^* = \frac{G_i}{G_{lr}}, \quad i = d, \text{ } dc \text{ or } p \quad (3)$$

The G_p^* value was seen as the true shear modulus ratio of the CLT panel. The G_p^* was used as a reference value which the simulated diaphragm shear simulation and diagonal compression simulation were compared to.

2.2 Experimental test

Experimental testing was performed to confirm the FE simulations. Only the diaphragm shear test and diagonal compression test were tested. The pure shear method had the issue of how to attach the load without restricting the displacements, which makes the pure shear method technically difficult to perform. During the diaphragm shear tests, no CLT panels were damaged or broken. The test started with the diaphragm shear test, and then, the core was cut and tested in the diagonal compression test, as shown in Fig. 1a and b. The tested CLT panels were produced by a factory using boards of equal dimensions and layup as FE simulated models. The CLT panels were glued with a polyurethane glue.

Nine non-edge glued 5-layer CLT panels with dimensions of 1500 × 500 × 130 mm (height × width × thickness), with an arranged main laminate direction for the odd and even numbered layers as shown in Fig. 1a, were tested. All nine CLT panels were cut from two larger CLT panels in a

45° angle. Hence, the main laminate directions shown in Fig. 1a were achieved for the tested CLT panels. The CLT panels were built of C24 strength graded Norway Spruce (*Picea Abies*) boards according to SS-EN 338:2016 [20]. From four-point flexural test (SS-EN 408 [6]) of 360 clear wood samples, mean E_l was calculated to 10,601 MPa with a coefficient of variation (COV) of 25.7%. The moisture content was measured by the oven-dry method to 7.1%. The density at the specified moisture content was measured to 432 kg/m³. By using the measured mean E_l and the earlier described material ratio, G_{lr} was calculated to 665 MPa. The displacements were measured in the central region on both sides of the CLT panels, as shown in Fig. 1a. The measured displacements $\Delta d_{active,i}$ and $\Delta d_{passive,i}$ were a mean value of the two measured sides, as shown in Fig. 2. The distance between the measuring points, $L_{M,dr}$ was the same as the FE simulation. Between the CLT panel and the supports, a plastic sheet was inserted to reduce the friction and allow the CLT panel to expand in the x-direction, as shown in Fig. 1a. Due to the unknown maximum load, the loading was done in three cycles: 0 to 100, 0 to 200, and 0 to 300 kN. The displacements were measured within the loading range of 100 to 160 kN for the second and third loading cycles. The first loading cycle was made to let the CLT panel settle between the supports. The levels of the measuring range were set to assure all tested CLT panels had linear correlations between the measured load and displacements. The displacements were calculated as average values from the linear regression lines within the measuring range for each loading cycle. The G_d and G_d^* were calculated according to Eq. (1) and (3), respectively.

Fig. 3 Diaphragm shear test with attached displacement transducers

Fig. 4 Diagonal compression test with attached displacement transducers

An Omegadyne LC412-75 K and Vishay HS25 were used to measure the force and displacements, respectively. The diaphragm shear test is shown in Fig. 3.

To make the CLT panels suitable for the diagonal compression test, the CLT panels were reduced in size as shown in Fig. 1b. The dimensions of the CLT panels became 354 × 354 × 130 mm for the height × width × thickness, respectively. The displacements were measured in the same position as the FE simulation. The diagonal compression test was performed by cycling the load from 0 to 50, 0 to 100, and 0 to 150 kN on the CLT panels. As previously described for the diaphragm shear test, the first cycle was neglected, and the displacements were measured in a similar way as described for the diaphragm shear test. The measuring range was 55 to 75 kN. The G_{dc} and G_{dc}^* were calculated according to Eq. (1) and (3), respectively. To measure the force and displacements, an Omegadyne LCHD-100 K and Vishay HS25 were used, respectively. The diagonal compression test is shown in Fig. 4.

3 Results and discussion

The results from the FE simulations are presented in Table 1. All three simulated methods yielded almost the same G^* value for the edge glued CLT panels. A minor overestimation could be seen for G_{dc}^* in the case of edge glued. The reason for this was suspected to be the small CLT panel size as the equation to calculate G_{dc} is based on larger CLT panels. The result for the edge glued CLT

Table 1 Shear modulus, G_i , [MPa] and shear modulus ratio, G_i^* , [unitless] for the simulated FE-models

	Non-edge glued	Edge glued
G_d (G_d^*)	573 (0.86)	665 (1.00)
G_{dc} (G_{dc}^*)	500 (0.75)	677 (1.02)
G_p (G_p^*)	475 (0.71)	665 (1.00)

panels in the diagonal compression simulation and the pure shear simulation was as expected and presented earlier by Turesson et al. [3, 8].

The shear modulus ratio for the non-edge glued CLT panels during pure shear should be 0.81 according to Turesson et al. [3]. In this study, the simulation resulted in a value of 0.71 as shown for G_p^* in Table 1. This difference, compared to Turesson et al. [3], was due to the low number of full-sized boards in the square CLT panel. In the pure shear simulation, only five of the fifteen boards were in full-size (180×30 and 158×20 mm), see the board layup in Fig. 1a-c. The other ten boards were narrower due to the size of the square CLT panel as shown in Fig. 1b-c. Because of this board size reduction, the measured G^* will be decreased. By calculating the size of the mean contact area based on the number of the boards (in this case, nine contact areas between two layers), $(b/\sqrt{2} \times b/\sqrt{2})/9 = 13,888.9 \text{ mm}^2$, and assuming square contact surfaces, the mean width of the contact surface will be approximately 118 mm. Based on this estimated mean board width and the board thicknesses, a G^* of 0.73 can be expected according to Turesson et al. [3]. This value corresponds better to the simulated value of non-edge glued G_p^* which became 0.71, as shown in Table 1. This means that the simulated value of non-edge glued G_p^* presented in Table 1 does not correspond to the actual board dimensions due to the low number of full-sized boards. This leads to the fact that the expected value of non-edge glued G_p^* should be increased to 0.81, as presented by Turesson et al. [3]. This increase of G_p^* is done because it is not the G_p^* of the analysed CLT sample that is sought, it is the G_p^* for a non-edge glued CLT panel with the specific board dimensions 180×30 and 158×20 mm. This means that the size of the CLT panel

used in the diagonal compression test and the pure shear simulation is not representative for a larger CLT panel with the specified board dimensions.

The diaphragm shear simulation resulted in a 6.2% higher shear modulus ratio (G_d^*) compared to G_p^* based on Turesson et al. [3]; see Table 1 and $G_p^* = 0.81$. This comparison was done because the results from Turesson et al. [3] was seen as the expected shear modulus ratio for the CLT panels.

Even though the CLT panel simulated in the diagonal compression test and the pure shear simulation does not represent the CLT panel simulated in the diaphragm shear test, the general deformations can be compared. This comparison is possible because, during pure shear, only the magnitude of the diagonally stretch and compression is affected by the load and G_p . By illustrating the result for the pure shear simulation relative-to-maximum, the global deformations become independent to the load and G_p . The simulated deformation of the three different methods is shown in Figs. 5 and 6. All three methods deformed the CLT panel in the x-direction, but in different appearances. A homogeneous deformation was seen for the pure shear simulation compared to the diagonal compression simulation. The neutral deformation line (zero deformation line) in the pure shear simulation did not follow the vertical diagonal. Due to the board arrangement, the neutral deformation line was offset. The simulated CLT panel contained three boards in each layer. One of the boards had a width of one finite element. This thin board was excluded from the visualisation in Figs. 5c and 6c due to its non-proportional deformation. The x- and y-displacements for the diagonal compression simulation showed that the CLT panel rotated between the two supports. This rotation was due to the main laminate directions of the layers. In this

Fig. 5 The relative-to-maximum displacement in x-direction for the CLT panel simulated in diaphragm shear simulation **a**, diagonal compression simulation **b**, and pure shear simulation **c**

Fig. 6 The relative-to-maximum displacement (neglected direction of displacement) in y-direction for the CLT panel simulated in diaphragm shear simulation **a**, diagonal compression simulation **b**, and pure shear simulation **c**

case, the odd layer proportion was 69% and the even layer proportion was 31%. Compared to the pure shear simulation, the neutral deformation line was more aligned with the force direction.

Due to the more uniform load application in the diaphragm shear test, the deformations became more evenly spread in the central region. This can be seen by comparing Figs. 5a and 6a to Figs. 5b and 6b. The deformation picture of the diaphragm shear simulation was more similar to the pure shear simulation. The main difference between the diaphragm shear simulation and the pure shear simulation was the level of deformation in the x-direction, see Fig. 5a. A larger range of deformation (+1.0 to −2.0) was seen in the diaphragm shear simulation. As seen in Fig. 5a, the neutral deformation line was moved compared to the pure shear method (Fig. 5c). A reason for this movement was the rotation of the CLT panel. This rotation did not

occur in the pure shear simulation because in this method, the CLT panel was sheared (not compressed).

The results from the experimental tests are presented in Fig. 7. The highest mean G^* was measured as 0.97 (mean $G_d = 648$ MPa) in the diaphragm shear test. The mean G^* was measured as 0.80 (mean $G_{dc} = 532$ MPa) for the diagonal compression tests. Due to the higher measured results, compared to the FE simulation, both the diaphragm shear test and diagonal compression test indicated that the tested CLT panels were partly edge glued. Based on the diaphragm shear test and the assumed material ratio between G_{lr} and the measured mean E_{lr} , the CLT panels were almost fully edge glued. By assuming a different material ratio, this situation would change. This situation of fully edge glued CLT panels was dismissed by a visual inspection of the tested CLT panels. Another reason could be that the CLT panels were damaged during the diaphragm shear test and due to that, a

Fig. 7 Individual CLT panels tested in the diaphragm shear test and the diagonal compression test

lower G_{dc} was measured. The authors believe that small ruptures may have been created, but not large enough to affect the result in the diagonal compression test. If larger ruptures had occurred in the tested samples, the load versus displacement curves in Fig. 8 would not have been linear.

It is unknown how the deformation of the CLT panel changes during the diaphragm shear test due to the stiffness variation. A small change in deformation will give a larger change of G^* as G^* is calculated from the slope of the load versus displacement curves. In a previous study by Brandner et al. [9], this effect was not reported, but a wide range of the COV (from 2.6% to 12.4%) was presented for the calculated shear modulus. If the CLT panel deforms nonuniformly (including the central region), the deformations measured in the central region will not be correct. The material data used in the FE models have no stiffness variations and therefore, it is seen as an ideal condition. Hence, the deformations will be uniform in these models. The previous described situation can also occur for the CLT panels tested in the diagonal compression test, but a major difference between the diagonal compression test and the diaphragm shear test is the position of the measured displacements. For the diaphragm shear test, the displacements were measured in the central region, representing 26.7% of the total height of the CLT panel. If the deformation is not uniform on the total height, the measured displacements in the central region will be affected. It is also unclear if there was any locking effect due to the vertical compression of the CLT panel and how partly glued side edges would affect the measurements. Locking effect means that the side edges are locked to each other. Therefore, if side edges are partly glued or locked, a non-edge glued CLT panel may behave like an edge glued one. In this study, no FE model was created with friction between the side edges; therefore, a locking effect cannot be concluded. From an earlier study by Turesson et al. [8],

partly glued side edges affected the result measured in the diagonal compression test.

The COV was calculated to 10.8% in the diagonal compression test and 5.0% in the diaphragm shear test. A large variation for the diagonal compression test was earlier concluded by Turesson et al. [7]. The reason for differences in result may be due to the fact that only a quarter of the central region in the diaphragm shear test was used as the central region for the diagonal compression test. This difference could be an explanation of the higher CV for the diagonal compression test. For both the diagonal compression test and the diaphragm shear test, the mean slope of the load versus displacement curves was changed by a small reduction of 3% and 1.5%, respectively, between loading cycle two and three. It is unclear if this reduction was because of small ruptures or a delay in recovery between the loading cycles.

The result for each CLT panel in both methods is presented in Fig. 7. Both methods showed different trends for the shear modulus. This could be due to the material variations. The CLT panels tested in the diagonal compression test were in fact a small part of the CLT panels tested in the diaphragm shear test. It was possible to achieve an equal mean value by decreasing the adjustment factor, α_d , from 1.0 to 0.82, but this would also decrease the simulated G_d^* (from 1.0 to 0.82, see G_d^* in Table 1) for the edge glued CLT panels, which would be an incorrect value.

Load versus displacement curves for the two methods are shown in Figs. 8–9. The load versus displacement relations had less spread for the diaphragm shear test and were straighter compared to the diagonal compression test, see Fig. 8 compared to Fig. 9. This spread was shown earlier by the COV values. Small irregularities can be seen in Fig. 8 for both the active and the passive directions. These small jumps are believed to be due to small ruptures/stress releases in the CLT panel.

Fig. 8 Load versus displacement curves of the second and third loading cycles for the diaphragm shear test

Fig. 9 Load versus displacement curves of the second and third loading cycles for the diagonal compression test

The Load versus displacement curves in Fig. 9 for the diagonal compression test showed a large spread of the measured results in the passive direction. This has earlier been reported by Turesson et al. [7]. It could also be seen in Fig. 9 that rupture occurred in the passive direction at a load of approximately 140 kN. The other irregularities seen in the active direction are believed to be because of the sample-support adjustments before all layers are fully loaded.

4 Conclusion

In this study, three different methods for measuring the shear modulus, G , of CLT panels were analysed. The three methods were the diaphragm shear test, the diagonal compression test, and the pure shear method. These methods were analysed by finite element simulations and two of them were also experimentally tested. The finite element simulations of non-edge glued CLT panel models showed that the pure shear simulation and diagonal compression simulation resulted in an almost equal G . The diaphragm shear simulation resulted in a slightly higher G . This result might occur because the diaphragm shear simulation was a more complex finite element simulation. For edge glued CLT panel models, all three methods resulted in comparable G .

The deformation picture of the CLT panels simulated in all three methods differed. The reason for this was how the loads were applied and how the supports affected the CLT panels. A rotation of the CLT panels between the supports was seen in both the diaphragm shear simulation and the diagonal compression simulation. This effect could not be seen for the CLT panels simulated in pure shear conditions.

Nine non-edge glued CLT panels were tested in both the diaphragm shear test and the diagonal compression

test. The CLT panels were first tested in the diaphragm shear test, and afterwards the central region was cut-out and tested in the diagonal compression test. This process was done to ensure that the same measuring region was used in both methods.

In theory, the diaphragm shear test was more similar in deformation behaviour to the pure shear simulation. This means that the shear state in a CLT panel is purer in a diaphragm shear test than in a diagonal compression test. The result from the experimental diaphragm shear test indicated that the tested CLT panels were almost fully edge glued (based on the used material ratio). No CLT panel was fully edge glued, but they could be partly edge glued at some points. The measurements from the diagonal compression test also indicated edge glued side edges, but at a lower level compared to the diaphragm shear test measurements.

The goal of the measured result is to be representative for a CLT panel built by a specified board dimension and quality. The panel size is crucial to get a representative CLT panel. A reduced G was estimated in the diagonal compression test and the pure shear simulations due to a too small CLT panel size. This means that the core part from the CLT panel tested in the diaphragm shear test was not representative for the specified board dimensions.

Brandner et al. [9] have successfully measured G and the shear strength by the diaphragm shear test. Other sources [8, 10, 17, 18] have earlier been able to measure G , not the shear strength, by the diagonal compression test. In this study, the experimental results from the diagonal compression test were seen more reliable compared to the pure shear method, even by considering the reduction of G due to the panel size. By correcting G_{dc} for the size, the measured result in the diagonal compression test is closer to the expected G_p (based on Turesson et al. [3]). Due to partly edge gluing, the authors suspect that nonuniform deformation of the CLT panels tested in the diaphragm

shear test was the reason for the deviating result. However, in ideal conditions, the diaphragm shear test was seen as the more reliable method due to the higher proportion of pure shear within the central region and the possibility of achieving the shear strength.

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Declarations

Conflict of interest The authors declared that there is no conflict of interest.

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