Influence of laminate direction and glue area on in-plane shear modulus of cross-laminated timber

Jonas Turesson¹ · Zahra Sharifi¹ · Sven Berg¹ · Mats Ekevad¹

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Abstract

The use of cross-laminated timber (CLT) in constructing tall buildings has increased. So, it has become crucial to get a higher in-plane stiffness in CLT panels. One way of increasing the shear modulus, G , for CLT panels can be by alternating the layers to other angles than the traditional 0° and 90° . The diagonal compression test can be used to measure the shear stiffness from which G is calculated. A general equation for calculating the G value for the CLT panels tested in the diagonal compression test was established and verified by tests, finite element simulations and external data. The equation was created from finite element simulations of full-scale CLT walls. By this equation, the influence on the G value was a factor of 2.8 and 2.0 by alternating the main laminate direction of the mid layer from the traditional 90° to 45° and 30° , respectively. From practical tests, these increases were measured to 2.9 and 1.8, respectively. Another influence on the G value was studied by the reduction of the glue area between the layers. It was shown that the pattern of the contact area was more important than the size of the contact area.

Keywords Cross-laminated timber · Diagonal compression test · Laminate direction · Shear modulus · Finite elements · Glue

1 Introduction

A cross-laminated timber (CLT) panel is a building component used for a variety of purposes such as walls, floors, roofs and beams [1]. CLT is a panel built by boards in a cross wise arrangement in a specific number of layers. Normally an odd number of layers 3, 5 and 7 is used, but also CLT with an even number of layers 2, 4 and 6 is possible. Boards used to construct CLT panels are based on strength class and dimension. The material and size of the boards will determine the properties of the CLT panel [2]. One important property of the CLT panels is the in-plane shear stiffness characterised by the shear modulus, G . This is not interchangeable with the shear modulus of wood because shearing of a CLT panel does not necessarily mean shearing of the wood. G is important for CLT walls

if they are used as shear walls to resist lateral movements of buildings. Lateral (shear) stiffness is important, and it is necessary to have sufficient lateral stiffness, especially for tall wooden buildings [3]. Several parameters affect the shear stiffness in a CLT panel. Important parameters are constituent board dimensions, board strength class, possible gaps between boards, gluing method and gluing area and the number of layers that build the CLT panel [4]. Traditional CLT panels use cross wise laminate directions, meaning directions 0° , 90° , 0° and so on as directions of the laminates. Two possible gluing methods are used for CLT panels. One is to glue only the flat sides of the boards, and the other one is to glue both flat and side edges. For the CLT panels glued on both flat and side edges of the boards, G will be equal to the shear modulus of solid wood [5]. Omitting side edge gluing means that G will be lower

✉ Jonas Turesson, jonas.turesson@ltu.se | ¹Department of Engineering Sciences and Mathematics, Division of Wood Science and Engineering, Skellefteå Campus, Luleå University of Technology, Forskargatan 1, 931 77 Skellefteå, Sweden.

than the shear modulus for solid wood. Using main laminate directions different from 90° in the mid layer is an interesting possibility to increase G , and that is the focus of this study.

The effect of the board dimensions on G for 3- and 5-layer panels has been studied earlier by Turesson et al. [4]. Other studies have concluded that board dimensions affect G but not analysed how much. Some studies have calculated G from different variants of the picture frame testing method; see [6–9], and others have used the diagonal compression test method [5, 6, 10, 11]. Recently, a method similar to the diagonal compression test has been used, but in a more sophisticated way [12, 13]. In the study by Bosl [7], 5-layer panels with the mid layer arranged at 45° have been analysed, both in theory and practice. In this study, a doubled G was presented by changing the main laminate direction of the mid layer from 0° to 45° . This is the only study found where the influence on G by an alternative main laminate direction has been tested.

The diagonal compression test method, which is analysed in this study, contends to define the shear stress occurring in the diagonally compressed sample. To calculate the shear stress in a diagonally compressed CLT panel, an isotropic model without any layers and gaps between boards has been used [6, 11]. In [6], this was the reason for the less accurate result from the diagonal compression test. The isotropic shear stress has been adjusted in [5] where the equation for calculating G was created based on FE (finite element) simulations. The limited scope in [5] resulted in a restricted equation which is only valid for the specific sizes and conditions occurring in the study and not in a general case. In [10], an equation suitable for a perfect shear condition has been used, but this situation does not occur during a diagonal compression test [6]. This method of assuming a perfect shear condition has been used earlier for other orthotropic materials like masonry [14], but the conditions for CLT panels are not equivalent.

The diagonal compression test is a relatively simple method which can be used to measure shear stiffnesses of CLT panels. However, there is a need for a suitable equation to calculate G from the measured stiffnesses where

the size of the CLT panels and the measured areas are arbitrary.

The aim of this study is twofold: first, to conduct FE simulations and tests to develop an equation for calculating G by diagonal compression test for CLT panels, and second, to use this equation to calculate G for non-edge glued 3-layer CLT panels with varying main laminate directions in order to maximise G . Also, to show the effect on G by reduction of the glued areas in CLT panels. No earlier study has shown this effect.

2 Method

Three variants of CLT panels with different main laminate directions were the basis for the study. Layers one, three and five were called the odd layers, and layers two and four were called the even layers. Layers two and three were called the mid layer for the 3- and 5-layer CLT panels, respectively. The main laminate direction of a layer was the direction of the wooden fibres of the boards that built the layer. All CLT panels were non-edge glued. CLT panels with a cross wise board layup were called “ordinary”, and CLT panels with the main laminate direction of 30° and 45° for the mid layer were called “non-ordinary”; see Table 1. Gaps between neighbouring board edges (“Gp”) were used to assure non-edge glued panels. Each panel was named according to the main laminate direction of the mid layer. Panels 3L30Gp, 3L45Gp and 3L90Gp had board dimensions representing a $\frac{1}{2}$ scaled version of a commercially used CLT panel. These CLT panels were used in the diagonal compression test and FE simulations. A full-scale CLT panel named 3L90 was also created and analysed in FE simulations. This CLT panel had dimensions twice as large as the $\frac{1}{2}$ scaled CLT panels. Two additional CLT panels denoted 3L90M and 5L0M, where “M” means manufactured, were used in the practical test and FE analysis for confirmation of the results.

The 3L30Gp, 3L45Gp and 3L90Gp CLT panels had controlled board positions. This means that the boards were arranged symmetrically around the midpoint of all layers,

Table 1 Analysed CLT panels

Name	No. of layers	Main laminate directions	Gap between side edges [mm]	$w_{board} \times t_{board}$ [mm]	Panel size $L_T \times L_T \times t$ [mm]
3L30Gp	3	$0^\circ/30^\circ/0^\circ$	1	75×15	$600 \times 600 \times 45$
3L45Gp	“	$0^\circ/45^\circ/0^\circ$	“	“	“
3L90Gp	“	$0^\circ/90^\circ/0^\circ$	“	“	“
3L90	“	“	0	150×30	$1200 \times 1200 \times 90$
3L90M	“	“	“	190×40	$1200 \times 1200 \times 120$
5L0M	5	$0^\circ/90^\circ/0^\circ/90^\circ/0^\circ$	“	220×46	$700 \times 700 \times 230$

as shown for the mid layers in Fig. 1a–c. The boards in the odd layers were arranged with the main laminate direction at 0° , as shown in Fig. 1d. The 3L90, 3L90M and 5L0M CLT panels were created without controlled board position.

2.1 Diagonal compression test

In the diagonal compression test method, a square CLT panel was compressed in one diagonal direction by a displacement controlled hydraulic jack. Please refer to [5, 6] for more details on the test procedure.

During a diagonal compression test, only one diagonal was compressed, and the second diagonal was left without control of the displacement. This created an uneven deformation of the sample and gave two different load versus displacement relations, one for each diagonal. There were two choices for the loading direction since all square CLT panels had two equal diagonals. For the ordinary CLT panels where the board lay-up was cross wise

directed (e.g. 0° , 90° and 0°), the two choices of loading direction were arbitrary, as shown in Fig. 2a. This means that the shear stiffness of an ordinary CLT panel did not depend on the choice of the compressed diagonal. However, this was not the case for non-ordinary CLT panels, as shown in Fig. 2b and c. Testing on one of the diagonals for 3L30Gp or 3L45Gp would result in a compression similar to the ordinary CLT panel i.e. in somewhat “cross-fibre” direction, cf. Figure 2b for CLT panel 3L45Gp. The situation changed in the case of compressing the other diagonal, where the compression in the mid layer would be in somewhat “fibre” direction, cf. Figure 2c for CLT panel 3L30Gp. So, in the testing of 3L30Gp and 3L45Gp, both the fibre and the cross-fibre directions were tested.

The two supports illustrated in Fig. 2a–c. had the same dimensions. The contact length between one side of the support and the thickness side of the CLT panel was 110 mm out of the total support length, L_s , 130 mm due to the cut off corner, as shown in Fig. 2a–c. The length

Fig. 1 Board positions for the mid and odd layers of 3L30Gp, 3L45Gp and 3L90Gp CLT panels. The non-ordinary CLT panels with the main laminate direction of the mid layer at 30° and 45° are presented in (a) and (b), respectively. The ordinary CLT panel with the

main laminate direction of the mid layer at 90° is shown in (c). The odd layers with the main laminate direction at 0° are shown in (d). The dashed line illustrates the symmetry axis, and the colours indicate the boards with equal dimensions in each panel

Fig. 2 An ordinary CLT panel compressed in the direction named cross-fibre (a), a non-ordinary CLT panel compressed in the direction named cross-fibre (b), and a non-ordinary CLT panel com-

pressed in the direction named fibre (c). Grey scale shows the main laminate directions and the central region where the displacements were measured

between the measuring points was denoted L_M , and the side length of the CLT panel was denoted L_T . Relative linear displacements were measured along the two diagonals as described earlier in [6]. The displacements were always seen as positive values independent of compression or extension. The displacements in the force direction and the perpendicular-to-force direction, Δ_{active} and $\Delta_{passive}$ respectively, were the changes of L_M , as shown in Fig. 2a. In [6], the square area defined by the measuring points was called the central region of the CLT panel, as shown in Fig. 2a. The size of the central region was described by the ratio between the area representing the central region and the total area of the panel. In [5, 6, 11], the central region was 16%. A central region of 37% was used in this paper for 3L30Gp, 3L45Gp, 3L90Gp and 3L90 variants and 66% and 45% for 3L90M and 5L0M, respectively.

2.2 Finite element analysis

The CLT panels were built in FE models by adding multiple boards with dimensions shown in Table 1. To be able to fit the CLT panels in the diagonal compression test setup, the length of 20 mm of the corners was removed, as shown in Fig. 2.

Material data for wood were obtained from the Swedish standard for the material classification [15] and defined by ratios between moduli in different directions and the longitudinal (fibre) direction. A mean value for longitudinal elastic modulus, E_l , was used for all orthotropic models in this paper. It was obtained from four-point flexural tests on cut-out samples from the CLT panels used in the diagonal compression test. The ratios of the radial modulus of elasticity E_r/E_l , the shear modulus G_{lr}/E_l and the rolling shear modulus G_{rt}/G_{lr} were 0.0336, 0.0627 and 0.10, respectively. The tangential modulus of elasticity, E_t , and the shear modulus G_{lt} were equal to E_r and G_{lr} , respectively. Poisson's ratios were set to zero due to the recommendation in the Swedish standard [16]. To reduce the calculation time, a symmetry condition was used in the thickness direction of the CLT panels.

A contact condition was applied on all glued surfaces. Slip, separation and penetration between surfaces in contact were prohibited for all glued surfaces. Glued surfaces were assumed full or reduced. Reduced contact surfaces in 3L30Gp, 3L45Gp and 3L90Gp CLT panels were modelled for simulations of poor gluing. Two alternatives for modelling reduced contact surfaces were used. The most favourable way (with respect to retaining twisting stiffness) of reducing the surface was to remove the central part (named B in Fig. 3) of each contact surface and keep the contact condition on only the outer part of the surface (named A in Fig. 3). The most unfavourable way (with respect to twisting stiffness) was to remove the outer part

Fig. 3 The reduced contact surfaces for the models representing the 3L30Gp CLT panels

of the surface (named A in Fig. 3) and keep the contact conditions on the central surface (named B in Fig. 3). The glued area was measured for each tested CLT panel, and both favourable and unfavourable FE simulations were conducted. Models with both surfaces A and B glued were simulated for all CLT panels.

All FE simulated models are listed in Table 2. For the diagonal compression test simulations, models representing an ordinary CLT panel were simulated only in the cross-fibre direction. The non-ordinary models were simulated in both the fibre and the cross-fibre directions. All diagonally compressed models were simulated with a global mesh size according to Table 2 and C3D20R cuboid elements in the commercial ABAQUS FE programme [17]. The relative linear displacements were measured as described earlier in Sect. 2.1.

2.2.1 FE simulations of full-scale CLT walls in order to get G

The problem of calculating G for a CLT wall was addressed by comparing two kinds of FE simulations. At first, an FE model of the CLT wall in full-scale was created as previously described with the same board dimensions as presented in Table 1. The CLT wall was deformed by a surface traction force and the resulting mean shear displacement, Δx as shown in Fig. 4, was noted. Then a model (with isotropic material properties) of the same CLT wall was modelled as a solid continuum with no boards. The isotropic wall model was created with the same outer dimensions and loaded with a surface traction force as the corresponding CLT wall model. An isotropic material model was chosen because CLT, in a general case, does not have a specific material direction. An isotropic material also made it easier to achieve G . The modulus of elasticity for the isotropic wall was set to E_l (same as for the CLT wall). Then, the shear modulus of the isotropic wall was varied and adjusted to

Table 2 Notations and properties of FE simulated models

Model		Side edge		Glued surface		Global mesh size [mm]		
		Gaps "Gp"	Glued "Eg"	A "Sa"	B "Sb"	Diagonal compression test	Full-scale CLT wall simulation	
							CLT wall	Isotropic wall
To define Eq. (1)	3L30GpSab ¹	x		x	x	10.0	$w_{board}/5$	$w_{board}/5$
	3L45GpSab ¹	x		x	x	"	"	"
	3L90EgSab ²		x	x	x	"	"	"
To verify Eq. (1)	3L30GpSa ¹	x		x		"	"	"
	3L30GpSb ¹	x			x	"	"	"
	3L45GpSa ¹	x		x		"	"	"
	3L45GpSb ¹	x			x	"	"	"
	3L90GpSa ²	x		x		"	"	"
	3L90GpSb ²	x			x	"	"	"
	3L90GpSab ²	x		x	x	"	"	"
	3L90Sab ²			x	x	"	"	"
	3L90MSab ²			x	x	"	$w_{board}/2.5$	$w_{board}/6.3$
	3L90MEgSab ²		x	x	x	"	"	"
	5L0MSab ²			x	x	"	$w_{board}/2.9$	$w_{board}/7.3$
	5L0MEgSab ²		x	x	x	"	"	"

¹ Model was simulated in the fibre and the cross-fibre directions² Model was only simulated in the cross-fibre direction

Fig. 4 FE simulation of a full-scale CLT wall with the resulting mean shear displacement, Δx . Arrows illustrate the surface traction force of 1 N/mm² applied on the top of the wall. The dashed box shows the area where the x-displacements are less affected by the outer edges of the wall. The dash-dotted box illustrates the dashed box after deformation. Grey scale shows the main laminate directions [mm]

give the same Δx as for the CLT wall model. The shear modulus obtained for the isotropic wall was assumed to be the G value of the CLT wall. By using this method, G values for all the CLT panels were calculated. By knowing the G values, an equation for calculating G in the diagonal compression test was obtained.

The dimensions of the CLT walls are shown in Fig. 4 for full-scale CLT wall models. The thickness of the CLT walls was based on the panel thickness. A surface traction force of 1 N/mm², illustrated with arrows in Fig. 4, was applied. The shear displacement, Δx , was measured in the x -direction as the mean displacement of the dashed box top surface illustrated in Fig. 4. This measured area was limited to get a displacement that was less affected by the right and left outer edges.

The main laminate direction of the odd layers for the ordinary and non-ordinary CLT panels was vertically directed in all CLT wall models, and for the non-ordinary panels, the main laminate direction of the mid layer was rotated in the clockwise direction. Due to limited computer power, different global mesh sizes were used for the CLT wall models. The global mesh size of the CLT wall and the isotropic wall models are shown in Table 2. All models were meshed with C3D20R cuboid elements.

A meshed deformation picture of the 3L45GpSab full-scale CLT wall simulation is presented in Fig. 5.

Fig. 5 x-direction deformation illustrated by the relative to the maximum displacement for the full-scale CLT wall simulation of 3L45GpSab

2.2.2 Calculation of G in the diagonal compression test

An equation to calculate G for the CLT panels tested in the diagonal compression test was created; see Eq. (1). The equation was defined by the force increment, F_{Inc} , for which the relative displacements Δ_{active} and $\Delta_{passive}$ were measured. This relationship between the F_{Inc} and Δ_{active} or $\Delta_{passive}$ was called the shear stiffness. The length between the measuring points, the side length of the CLT panel and the thickness of the CLT panel were denoted L_M , L_T and t , respectively. To get Eq. (1) size-independent, L_T , L_M and t were included in the equation. In the case of non-ordinary CLT panels, Δ_{active} and $\Delta_{passive}$ were calculated as the mean value from the compression of both the fibre and the cross-fibre directions. The equation was created based on EN 408 [18] using one adjustment factor, α_D , for each main laminate direction of the mid layer.

$$G = \alpha_D \frac{L_M}{2\sqrt{2}tL_T} \frac{F_{Inc}}{|\Delta_{active}| + |\Delta_{passive}|} [\text{MPa}] \quad (1)$$

This method of using EN 408 [18] for calculating the G value of the CLT panels was used earlier by Brandner et al. [12] and Silly [19] for a similar test method. The models used to evaluate α_D were 3L30GpSab, 3L45GpSab and 3L90EgSab, see Table 2. The value of α_D was calculated by using the G value (from full-scale CLT wall simulation) and the shear stiffnesses (from diagonal compression test simulation) achieved for each FE simulated model. To check if there was any influence from L_M or the support length, L_S , on G , four additional versions of 3L90EgSab were created. In two of them, the ratio L_S/L_T was changed from 0.11 to 0.05 and 0.22. In the other two, the ratio $L_M/(L_T\sqrt{2})$ was changed from 0.61 to 0.30 and 0.90.

A material-independent and dimensionless shear modulus, G^* , was calculated according to Eq. (2) in order to achieve a value suitable for comparisons between variants with different material properties. This value was calculated for all FE simulations.

$$G^* = \frac{G}{G_{lr}} \quad (2)$$

2.3 Confirmation of the G equation

Eleven CLT panels were built and tested in order to check the validity of Eq. (1). The panels were built of Norway spruce boards (*Picea abies*) classified to C24 according to the Swedish standard SS-EN 338:2016 [15]. The CLT panels were designed and built as 3L30Gp, 3L45Gp and 3L90Gp; see Tables 1 and 3 for dimensions and material properties. A standard polyvinyl acetate glue was used. The CLT panels were built by using less amount of glue than recommended by the glue manufacturer [20] in order to analyse the reduction of the glued areas effect on G . The CLT panels named 3L90M and 5L0M were built

Table 3 Material properties for the tested CLT panels with coefficient of variation (COV) within parentheses

Name	No. of CLT panels	E_f [MPa]	MC [%]
3L30Gp	3	11,685 (18.0%)	10.6
3L45Gp	4	"	"
3L90Gp	"	"	"
3L90M	"	9657 (16.9%)	9.9
5L0M	6	10,757 (15.5%)	8.7

Fig. 6 A CLT panel during the diagonal compression test with attached displacement transducers

Table 4 Maximum loading force F_{max} during the diagonal compression test in the cross-fibre direction and, within parentheses, in the fibre direction

Name	F_{max} [N]	Range [N]
3L30Gp	4800 (5500)	4000 to 4800
3L45Gp	10,000 (15,000)	5000 to 10,000
3L90Gp	13,000	"
3L90M	300,000	100,000 to 150,000
5L0M	350,000	200,000 to 300,000

The loading range for measuring the linear displacements Δ_{active} and $\Delta_{passive}$. The same range was used independent of the loading direction

of Norway spruce boards (*Picea abies*) by a manufacturer as described in Table 1. These CLT panels were glued with polyurethane glue and without reduction. All tested CLT panels were built without glued side edges. A total of 374 clear wood samples was used to measure the mean modulus of elasticity in the fibre direction, E_f . E_f was measured by the four-point flexural test according to the Swedish standard SS-EN 408 [18]. The moisture content (MC) was

measured by the oven-dry method. Material properties for the tested CLT panels are shown in Table 3.

2.3.1 CLT panels in the diagonal compression test

Tests were performed according to [6] where displacement transducers were used on the top side of the CLT panels, as shown in Fig. 6. Displacement transducers could not be used on the down side of the CLT panels due to the support for preventing downward bending. The displacement transducers were positioned according to the description presented earlier in Sect. 2.1.

The maximum force, F_{max} , and the measuring range for the Δ_{active} and $\Delta_{passive}$ displacements are presented in Table 4. All non-ordinary CLT panels were tested in both the fibre and the cross-fibre directions. The G value was calculated for all ordinary and non-ordinary CLT panels according to Eq. (1). No CLT panel was tested to rupture.

An Omegadyne LCHD-100 K and Vishay HS25 displacement transducers were used to measure the force and displacements, respectively. The accuracy of the force and displacement transducers were 200 N and 0.05 mm, respectively.

2.3.2 Reduction of the glue area

The size of the glued areas was measured after the diagonal compression test on the 3L30Gp, 3L45Gp and 3L90Gp CLT panels. The glue area percentage of the CLT panels was estimated by cutting out nine sample cubes (as shown in Fig. 7a) from each tested CLT panel. These sample cubes were separated in each glue line. A transparent grid sheet with a grid size of 10 × 10 mm was used to estimate the area of the glued contact surface, as shown in Fig. 7b. Each sample cube had a size of 80 × 80 × 45 mm.

The area of the grid was judged to be glued if a wooden failure was observed within the area. The glue area

Fig. 7 The position of the sample cubes in a CLT panel (a) and a transparent grid sheet on the glue surface of a separated sample cube to determine glue area percentage (b) [mm]

percentage was estimated by calculating the ratio of the number of squares in the grid containing wood failure and the total number of squares covering the glue surface. Then, the mean glue area percentage was calculated for each group of the CLT panels.

3 Result and discussion

The mean glue area percentage for 3L30Gp, 3L45Gp and 3L90Gp was measured to 51%, 47% and 59%, respectively. The COV of the mean glue area percentage was 16.3%, 15.1% and 13.1% for 3L30Gp, 3L45Gp and 3L90Gp, respectively.

The a_D factor was calculated from FE simulations to 7.15 and 6.56 for the 30° and 45° main laminate direction of the mid layers, respectively. The a_D factor for the ordinary CLT panels was calculated to 2.52. By using the a_D , the G values were calculated for the tested CLT panels; see Table 5. The highest G value was calculated for 3L45Gp, which also had a G^* value over 1.0. This means that the G value was higher than G_{II} in solid wood. This becomes possible because shearing of a CLT panel with non-uniform main laminate directions does not result in a pure shearing of the boards. The high G^* values for 3L90M and 5L0M indicate that the side edges were partly glued. This was also confirmed by a visual inspection of the tested CLT panels.

The G^* relative to 3L90Gp as a function of the mid layer main laminate direction is shown in Fig. 8 for 3L30Gp, 3L45Gp and 3L90Gp. An increase of G^* with a factor of 2.9 (from 0.36 to 1.05) was achieved by a rotation of the mid layer from 90° to 45°. An increase with a factor of 1.8 (from 0.36 to 0.65) was achieved by a rotation of the mid layer from 90° to 30°.

3.1 Evaluation of the shear modulus equation

With use of the a_D factor, the G^* values were calculated for the diagonally compressed models and the full-scale CLT wall simulations; see Table 6.

A reduction of G^* was seen for all three tested laminate directions due to the reduction of the contact area with glue; see the Sab models compared to the Sa and Sb models for the main laminate direction in Table 6. All three

Fig. 8 Material-independent and dimensionless shear modulus, G^* , and relative to 3L90Gp as a function of the main laminate direction in the mid layer for the 3-layer CLT panels (3L30Gp, 3L45Gp and 3L90Gp) with reduced glue area

ranges between the Sb and Sa were large, and for 3L45Gp and 3L90Gp presented in Table 5, the G^* values were within this range. The CLT panels 3L30GpSa, 3L45GpSa and 3L90GpSa had a similar G^* as 3L30GpSab, 3L45GpSab and 3L90GpSab, respectively. This showed that the pattern of the glue area between the layers was more important than the percentage of the glue area. The G value calculated from the full-scale CLT wall simulations corresponded to G_{II} when the side edges were glued; see the G^* value for 3L90EgSab, 3L90MEgSab and 5L0MEgSab in Table 6. This has been concluded earlier by Berg et al. [5].

The mean difference between the diagonal compression test simulations and the full-scale CLT wall simulations was 11.9%. The largest difference was calculated for 3L45GpSb where Eq. (1) underestimated the G value. This difference resulted due to the weaker cross-fibre direction measured in the diagonal compression test (see Fig. 2b). In the full-scale CLT wall simulation, the deformation as shown in Fig. 5 was more uniformly spread, independently of the contact area appearance. The same situation also occurred for 3L30GpSb. The third largest difference between diagonal compression test simulations and the full-scale CLT wall simulations was for model 5L0MSab. This reduction was due to the few boards per layer which built the CLT panel. The G^* values of the tested CLT panels 3L90M and 5L0M presented in Table 5 were within the range of non-edge glued and edge glued; see the G^* values for the diagonal compression test simulation in Table 6. This was also visually confirmed on the tested CLT panels that the side edges were partly glued.

Based on the board dimensions, the G^* value for 3L90Sab was estimated to 0.72 by Turesson et al. [4]. This value was close to and between the two G^* values from the diagonal compression test simulation and the full-scale CLT wall simulation; see 3L90Sab in Table 6. The same value of G^* as 3L90Sab was estimated by Turesson

Table 5 Shear modulus, G , and material-independent and dimensionless shear modulus, G^* , for the tested CLT panels in the diagonal compression test, with coefficient of variation (COV) in parentheses

Name	G [MPa]	G^*
3L30Gp	480.0 (9.3%)	0.65
3L45Gp	771.4 (2.2%)	1.05
3L90Gp	265.6 (12.1%)	0.36
3L90M	550.7 (7.3%)	0.91
5L0M	612.6 (15.6%)	0.91

Table 6 Material-independent and dimensionless shear modulus, G^* , from the diagonal compression test and the full-scale CLT wall simulation to verify Eq. (1)

	Model	G^* from diagonal compression simulation	G^* from full-scale CLT wall simulation	Difference
To define Eq. (1)	3L30GpSab	1.40	1.40	0%
	3L45GpSab	1.78	1.77	0%
	3L90EgSab	1.0	1.0	0%
To verify Eq. (1)	3L30GpSb	0.66	1.07	38.3%
	3L30GpSa	1.36	1.33	2.3%
	3L45GpSb	0.74	1.39	46.8%
	3L45GpSa	1.75	1.71	2.3%
	3L90GpSb	0.33	0.32	3.1%
	3L90GpSa	0.63	0.69	8.7%
	3L90GpSab	0.65	0.69	5.8%
	3L90Sab	0.71	0.75	5.3%
	3L90MSab	0.76	0.73	4.1%
	3L90MEgSab	1.08	1.0	8.0%
	5L0MSab	0.66	0.79	16.5%
	5L0MEgSab	1.01	1.0	1.0%

The absolute difference was calculated between the G^* values from the diagonal compression test and the full-scale CLT wall analysis

et al. [4] for 3L90GpSab but with neglected board gap. In this case, the calculated G^* values in the diagonal compression test simulation and the full-scale CLT wall simulation were lower than 0.72 due to the gaps between the boards. This reduction due to the gaps between boards was described earlier by Turesson et al. [4] and Moosbrugger et al. [21].

By using external data from another practical diagonal compression test [6], G^* resulted in 0.81 and 0.93 for the group of CLT panels named 3-layer R and 5-layer R, respectively. These values of G^* were estimated to 0.8 and 0.85, respectively, by Turesson et al. [4]. This shows that Eq. (1) with the α_D factor set to 2.52 correctly calculated G for the 3-layer R panels (G^* calculated to 0.81 and estimated by Turesson et al. [4] to 0.8) but was overestimated for the 5-layer R panels (G^* calculated to 0.93 and estimated by Turesson et al. [4] to 0.85). In the study by Turesson et al. [6], it is commented that the 5-layer R panels may have been partly edge glued. This would result in higher measured shear stiffnesses and then a too high calculated G .

Sensitivities of Eq. (1) from the side length of the CLT panel, L_T , the distance between measuring points, L_M , and the support length, L_S , are shown in Table 7. The G value is presented as the dimensionless shear modulus G^* in Table 7. Both ratios $L_M/(L_T\sqrt{2})$ and L_S/L_T influenced on G . There was a negligible sensitivity for a $L_M/(L_T\sqrt{2})$ ratio between 0.30 to 0.61. Higher ratios of $L_M/(L_T\sqrt{2})$ were negatively correlated to G . A linear negative correlation between L_S/L_T ratio and G was detected. The change, expressed in G^* , was linear and -0.03 per 0.06 change of L_S/L_T ratio.

Table 7 Sensitivity of Eq. (1) shown as the material-independent and dimensionless shear modulus G^*

Parameter	Parameter value	G^*
$L_M/(L_T\sqrt{2})$	0.30	0.99
	0.61	1.00
	0.90	0.93
L_S/L_T	0.05	1.03
	0.11	1.00
	0.22	0.94

Bold values are for the reference case 3L90EgSab

The G^* relative to 3L90GpSab as a function of the mid layer main laminate direction from full-scale CLT wall simulation is shown in Fig. 9 for 3L30GpSab, 3L45GpSab and 3L90GpSab. An increase of G^* with a factor of 2.6 (from 0.69 to 1.77) was achieved by a rotation of the mid layer from 90° to 45° . An increase with a factor of 2.0 (from 0.69 to 1.40) was achieved by a rotation of the mid layer from 90° to 30° . These increases (2.6 and 2.0) were similar to the increases achieved for the tested CLT panels with reduced glue area (2.9 and 1.8), as shown in Fig. 8. In the study by Bosl [7], a lower increase (2 compared to 2.6) was seen. One difference between this study and that of Bosl was the proportion of layers with a 45° main laminate direction. Bosl used CLT panels, where the 45° mid layer corresponded to 1/5 of the CLT panel thickness. In this study, the ratio was 1/3. Due to the higher proportion of layers with a 45° main laminate direction, a larger increase of G was seen. Another reason

Fig. 9 Material-independent and dimensionless shear modulus, G^* , and relative to 3L30GpSab as a function of the main laminate direction in mid layer for 3-layer CLT panels (3L30GpSab, 3L45GpSab and 3L90GpSab models)

could also be that this study took the advantage of testing both diagonal directions of the CLT panel.

4 Conclusion

An equation (Eq. (1)) was established to calculate the shear modulus, G , for CLT panels. The equation was based on the shear stiffness from a diagonal compression test and a factor derived from finite element simulations.

By using the equation, the effect of reduced glue area between the layers was calculated. The results showed that the pattern of the glue area was more important than the size of the glue area. It was possible to make a large reduction of the glue area with almost no effect on G if the remaining glue area was located on the periphery. However, the reduction of G was large if the remaining glue area was in the middle.

The effect on G by varying the main laminate direction of the mid layer for a 3-layer CLT panel was also calculated. This means using the main laminate directions 0°, 30° and 0° and 0°, 45° and 0° (non-ordinary) instead of the traditional 0°, 90° and 0° (ordinary) directions. An increase of G for a finite element simulated CLT panel with a factor of 2.0 and 2.6 was achieved by rotating the mid layer to 30° and 45°, respectively. These factors were also measured to 1.8 and 2.9 on tested CLT panels. This large increase of G was due to the “bracing” effect of using the mid layer orientations (30° and 45°) arranged in the same direction as a traditional bracing. This means that by using non-ordinary main laminate directions, it is possible to increase G of CLT walls. Compared to ordinary CLT, non-ordinary CLT would, by less material, lead to a stiffer construction, which can be beneficial for tall buildings.

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Compliance with ethical standards

Conflict of interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

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