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IN-PLANE SHEAR: DESIGN OF A NEW PICTURE FRAME TEST CONFIGURATION

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ABSTRACT: The current in-plane shear test methods only apply to some variations of cross-laminated timber in development. This research aimed to design a test configuration to gauge a wide range of wood panel products. The chosen method is the picture frame test based on its potential to generate a pure shear field. Therefore, a connection is required that enables a uniform shear force transmission to the edges of the timber specimen. Notches along all four edges were designed. By calculation, the number, arrangement, and size of those notches were chosen to maximise the load-bearing capacity. The performance of practical tests validated the resulting test configuration. Series of 3- and 5-layer CLT were tested with a total of eight specimens. Results show that this kind of picture frame is effective and provides plausible values for the shear modulus, which aligns with the literature. In addition, model-accurate shear stiffnesses can be determined, which are used in structural analysis. Furthermore, preliminary tests with mechanically laminated timber, including diagonal lamination, were performed, and an in-plane shear failure could be achieved. Further tests will be necessary for parameter studies and statements about the potential applicability of other wood-based materials.

KEYWORDS: in-plane shear, picture frame test, notches, cross-laminated timber, mechanically laminated timber

1 – INTRODUCTION

Cross-laminated timber (CLT) is a well-established construction material, composed of orthogonally glued boards. Nevertheless, research and development to optimise CLT further is ongoing. Recent projects are investigating modifications like using hardwoods, disintegrated layers, diagonal lamination, or mechanical jointing of layers without glue. The use of those adapted CLT elements in structural applications usually requires an understanding of their in-plane shear behaviour.

Many different test procedures for measuring the in-plane shear capacity have been developed and discussed in the literature over the past few years. Serrano [1] provides an overview about the most relevant methods and addresses the ongoing debate surrounding the use of small-scale tests. On the one hand, single-node tests can be conducted in a cost-efficient manner in order to achieve the sought failure mode. On the other hand, the potential system effects of whole plates cannot be identified by these methods. In the meantime, full-scale experiments are complex and expensive, and there is currently no standardised procedure for testing on CLT-plates. [1]

This is why multi-node tests with medium-scale elements appear to be the most promising approach. Annex C of the EN 16351 [2] presents the standardised diaphragm shear test, which was first introduced by Kreuzinger and Sieder [3] and further developed by Brandner et al. [4]. Figure 1 illustrates the test configuration with the CLT rotated by 45° and the resulting stresses in the centre of the specimen. Due to the acting force, the mechanical state of the specimen is always under compression rather than pure shear, which must be accounted for in the subsequent evaluation [2–4].

In addition, the compression force is the reason why this testing method is only valid for orthogonally laminated CLT. If it were to be applied to diagonal laminated timber (DLT), the diagonal laminates could be oriented vertically, resulting in a pressure load in the longitudinal direction and the buckling of those diagonal layers. [5]

One method for generating a more ideal shear field in CLT elements would be the picture frame test. Björnfot et al. [6] presented a picture frame that was bolted along the edges of CLT elements with dowels. This method was found to be effective and resulted in a reasonable range of shear modulus. Turesson et al. [7] used the same method for more extended investigations and concluded that it is simple and gives good and reliable results with

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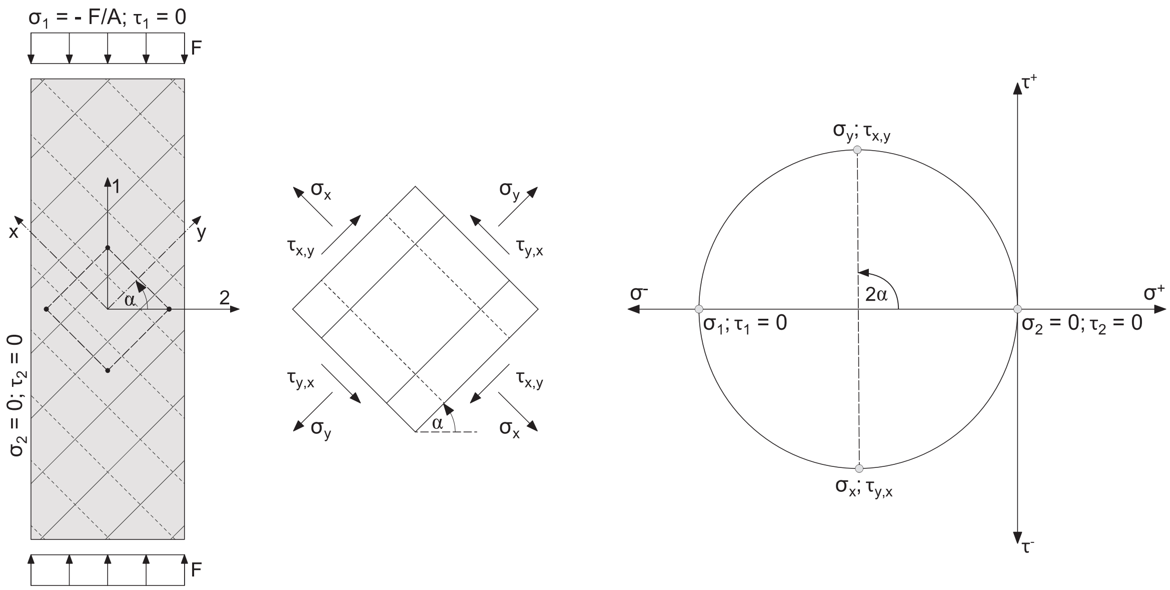

Figure 1: Diaphragm shear test configuration and the resulting stresses from Mohr's circle [2–4]

minor deviations. Further finite element (FE) modulations show that the picture frame test is applicable for generating a pure shear condition in CLT [8]. However, one issue was identified as the deformation of the bolts, which led to difficulties at the disassembly. Additionally, it indicates a non-uniformly load distribution along the edges [7].
To the best of the authors' knowledge, there are no reports in the literature on picture frame tests with DLT.

Consequently, the objective of this paper is to propose a valid modification of the picture frame test that allows in-plane shear tests with all kinds of wood panel products, independently of the disintegration, the orientation, and the joining of layers.

2 – THEORY

2.1 PICTURE FRAME TESTS

The main component of this test configuration is the metal frame developed by Holzinger [9] as part of his master's thesis. It consists of four rigid legs hinged at the corners via single bolts, as Figure 2 illustrates. This results in a frame that is significantly stiffer than the test specimens, thus enabling a constant load introduction over the length of the legs. The upper and lower bolts are fixed, thus ensuring that the frame can only deform along the centre axis. In an ideal model, the legs transfer the loads evenly over the edge of the precisely fitted test specimen, thereby creating a pure shear stress state.

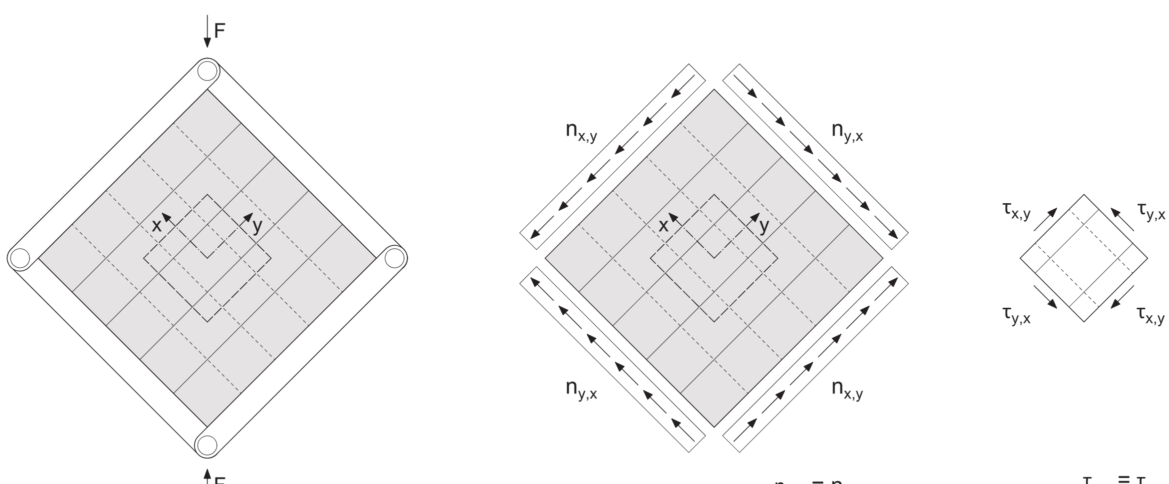

Figure 2: Principle of picture frame tests – left: picture frame under load with test specimen inside; middle: load on the test specimen; right: stresses on the differential element

If the plane is made of an isotropic and homogeneous material, the pure shear stresses will result in a shear deformation as shown in Figure 3. Based on this deformation, the shear modulus G can be defined as the ratio of the shear stresses τ and the shear strains γ.

$$G = \frac{\tau}{\gamma} \tag{1}$$

The shear strain γ is determined from the geometric ratios using the cosine rule:

$$(d - \Delta)^2 = a^2 + a^2 - 2a^2 \cdot \cos(90° - \gamma) \tag{2}$$

By considering small displacements ($\cos(90° - \gamma) \approx \sin(\gamma) \approx \gamma$; $\Delta^2 \approx 0$) and simplifying the equation ($d = \sqrt{2}a$) the shear strain can be expressed as:

$$\gamma = \frac{\sqrt{2}\Delta}{a} \tag{3}$$

The shear stress τ is defined as:

$$\tau = \frac{n_{xy}}{t_{CLT}} = \frac{F}{\sqrt{2} \cdot l} \cdot \frac{1}{t_{CLT}} \tag{4}$$

with n_{xy} as the shear force, l as the load introduction length and t_{CLT} as the total thickness of the CLT element.

The shear modulus G therefore is calculated to:

$$G = \frac{\tau}{\gamma} = \frac{F \cdot a}{\Delta \cdot 2 \cdot l \cdot t_{CLT}} = k \cdot \frac{a}{2 \cdot l \cdot t_{CLT}} \tag{5}$$

with shear stiffness k as:

$$k = \frac{F}{\Delta} \tag{6}$$

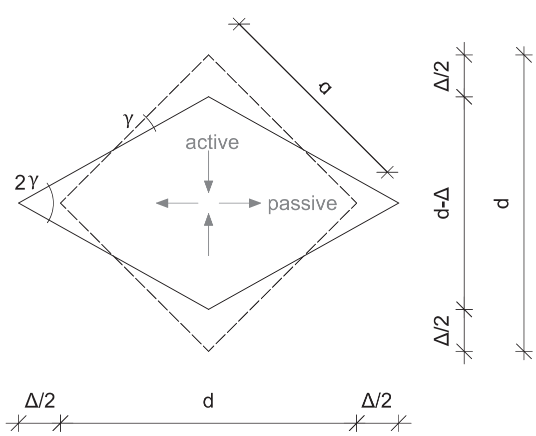

Figure 3: In-plane shear deformation of an ideal material

2.2 CONNECTION FOR LOAD TRANSFER

The connection between the steel frame and the CLT represents a crucial aspect in guaranteeing that the load is transferred uniformly to the test specimen in accordance with the theoretical uniform shear application. The closest approximation to the ideal model would be a glued connection. However, it should be noted that the laboratory effort required to implement this solution would be significant.

Turesson et al. [7] have previously demonstrated the efficacy of picture frame tests utilising bolts as connectors. However, this system may not be applicable to any type of laminated timber elements. In particular, specimens made of mechanically laminated timber (MLT), with nails, screws or dowels as fasteners, have a relatively low in-plane shear stiffness in comparison to glued CLT. The connection with bolts would interfere the edge areas and the behaviour of the whole element. Furthermore, the deformation of the bolts themselves could also present a challenge.

This is why an adaptation of the picture frame test is necessary. The selected method of load transfer is a series of notches on all four legs. Modelling and FE calculations indicate that a pure shear field can be achieved in the centre of the test specimen. In his master's thesis, Fricke [10] developed the final geometry of those notches. In consideration of the manufacturing process and the ease of installation, he selected the number, arrangement, and size in order to maximize the load-bearing capacity. Nevertheless, it is possible for the notches to shear off or be pressed over, causing the connection to fail before a shear failure can be induced. Figure 4 illustrates the final geometry. Since a suitable steel frame with smooth sides was already available, the steel counterparts of the notches were added to it. A reversible connection with high-strength pretensioned bolts was designed for this purpose.

3 – MATERIAL AND METHODS

3.1 PROCEDURE AND MEASURING

The final test setup is pictured in Figure 4. The square specimens have a side length of 1123 mm. In preparation, nine notches are milled into the edges. Furthermore, the corners are cut off to provide space for the bolts of the frame. Consequently, a load introduction length of 1015 mm on each edge remains.

The tests were conducted on the Zwick/Roell Z600 testing machine at the TUM MPA Bau, as pictured in Figure 5. The load was applied as pressure from above. In order to induce failure after 300 ± 120 s the tests were carried out at a speed of 6.0 mm/min. The displacements in active (vertical) and passive (horizontal) direction were measured in a square area with a side length of 500 mm in the centre of the specimens. This equates to approximately 45 % of the edge length or 20 % of the total area. On each of the two sides, different methods were applied to measure the displacements. On side 1, the changes in length of the diagonals of the area were measured using WayCon SX50 draw wire sensors (0.1 % accuracy). The area of side 2 was recorded by the LIMESS Q400 digital image correlation system (0.01 mm accuracy).

3.2 TEST SPECIMENS

In order to evaluate the functionality of the test configuration, different specimens were tested. The first series consisted of five test specimens of 3-layer CLT.

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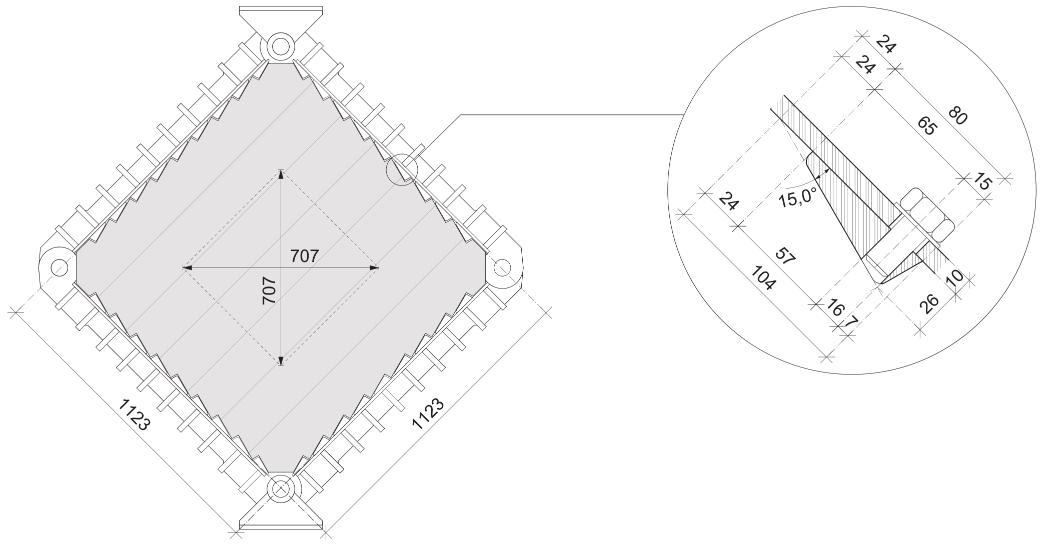

Figure 4: Picture frame test configuration with notches along the edges, all dimensions in millimetres

The planes were supplied by a major manufacturer. The specific properties of the individual lamellas are not known. However, at least 90 % of the boards are graded at C24 or above, as confirmed by the mean density of 442 kg/m³. The second series comprised three elements of 5- layer CLT. These test specimens were manufactured in the laboratory from lamellas with a mean density of 544 kg/m³.

Both series were manufactured without any gaps or stress reliefs. Only the flat sides were bonded. It is possible that partial bonding of the narrow edges occurred unintentionally due to the production process.

In addition to the glued cross-laminated timber elements, a series of eight mechanically laminated timber planes was investigated. The 5-layer arrangements, including two diagonal oriented layers, were joined together by 110 riffled aluminium nails per square metre and jointed layer. Those test specimens consisted of lamellas with

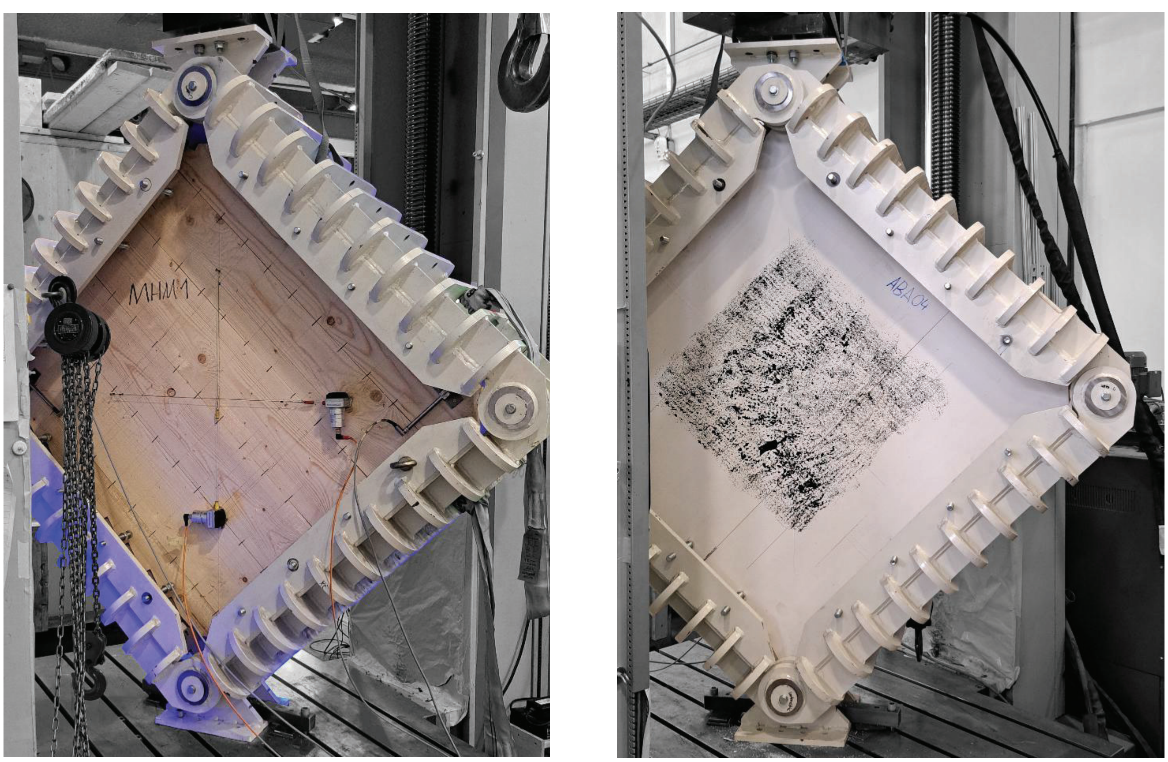

Figure 5: CLT elements in picture frame test setup; left: Side 1, right: Side 2

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Table 1: Pre-test program in the Picture Frame Test

		Layer	3-layer CLT	5-layer CLT	5-layer MLT
Number of panels	[-]		5	3	8
Number of layers	[-]		3	5	5
Orientation of layers	[°]		0 / 90 / 0	0 / 90 / 0 / 90 / 0	0 / 30 / 0 / 150 / 0
Mean density	[kg/m³]		442	544	419
Board thickness	[mm]	TL	20	40	22
		CL	20	20	22
		ML	-	20	22
Board width	[mm]	TL	230	120	125 – 281
		CL	115	120	148 – 256
		ML	-	120	149 – 271
Moisture content	[%]		10.9	10.2	12.0

TL = Top layer; CL = Cross layer; ML = Middle layer

varying board widths. As there are no references for such elements to date, the objective of this study was only to demonstrate whether mechanically laminated and diagonal laminated timber can also be investigated in this picture frame test configuration.
Table 1 summarises the properties and assemblies of the different series.
The final joinery of all test specimens was undertaken in the laboratory. In order to enable the installation of the test specimens in the frame, they were manufactured with dimensions approximately 2 mm smaller. All tests were initiated from a zero position, ensuring that all notches were in positive contact.

3.3 DATA AVAILABILITY AND ANALYSIS

The data publication by Fochler and Schumacher [11] provides access to all the data collected in this research project.
In accordance with EN 408 [12] and EN 16351 [2], the stiffness values are calculated with the measured displacements in the range from 10 % to 40 % of the maximum load according to (6). The mean stiffnesses are analysed for the active k_a and passive k_p directions, the two sides k_{s1}, k_{s2} and the entire element k_{s1s2}. The latter is then used in conjunction with (5) to determine the shear modulus G_{mean} of the test specimen.

4 – RESULTS

4.1 GENERAL OBSERVATIONS

The loading of each layer via the notches is consistent with their crosswise arrangement. Layers that are aligned perpendicular to the frame leg are subjected to transverse pressure, which results in ductile failure. In contrast, the parallel-oriented boards are loaded in the longitudinal direction, leading to brittle failure through shearing off the notches. This notch failure occurs in all CLT panels before in-plane shear failure takes place. Here, the two edges on which the cross layers are parallel to the frame leg are decisive. With a single longitudinal board and two cross layers, the mean strength of the notches in the 3-layer CLT is 217.0 kN (COV = 16.8 %). In the 5-layer CLT, the notches with two longitudinal boards and three cross layers achieve a mean strength of 535.4 kN (COV = 9.7 %). Although the cross-sectional area in the cross-direction doubles, the strength of the notches is higher by a factor of 2.4. The reason for this is the also larger cross-section subjected to transverse pressure. Subsequent analyses are conducted within the linear elastic range prior to the onset of notched failure.
Because of the notch failure, it is impossible to maintain a uniform load transfer. That is evidenced by the fact that the frame legs lose contact with the edges of the test specimen. The following load situation is a compression between the upper and lower corner. This scenario resembles the test configuration of a diagonal compression test, as described by [5, 7, 13, 14]. The consequence is a reduction in the purity of the shear field. Nevertheless, in-plane shear failure was achieved with the further increase in load.

4.2 CROSS LAMINATED TIMBER

Table 2 presents a summary of the mean stiffness values for each series. It can be observed that the stiffness of both CLT series is approximately 19 % higher in the passive direction than in the active direction. However, the spread of the measured displacements in the active direction is also higher, as in Figure 6 visualized.
A comparison of the two sides reveals that the absolute difference of 5.7 kN/mm in 3-layer CLT is neglectable. In contrast, the difference in stiffness between the two sides is 37.8 kN/mm for 5-layer CLT. Additionally, the COV of side 1 is relatively high. The orientation of the elements in the picture frame does not explain this behaviour. However, this circumstance is comparable with the results of Turesson et al. [7], who concluded this was due to varying material properties or a non-uniform load distribution across the width.
The mean shear modulus G_{mean} for the 3-layer panels was 526.6 MPa, and for the 5-layer panels 561.5 MPa. All 3-layer specimens showed net-shear failure. No in-plane shear failure was observed in the 5-layer CLT elements at a maximum load of 600 kN. However, the deformations that occurred up to this point also indicate net-shear behaviour.

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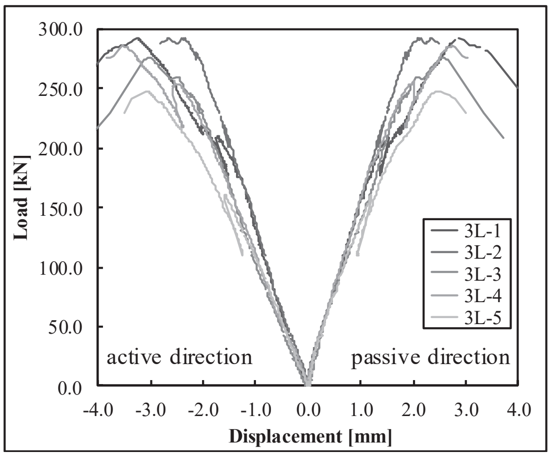
Table 2: Mean stiffness value k_i and mean shear modulus G_i with transducer combinations i of CLT and MLT elements

		Transducer combination	3-layer CLT	5-layer CLT	5-layer MLT
k_a	[kN/mm]	Active on side 1 and 2	118.8 (11.2 %)	293.9 (9.9 %)	36.2 (18.6 %)
k_p	[kN/mm]	Passive on side 1 and 2	- 140.1 (3.2 %)	- 350.0 (5.5 %)	- 62.1 (30.8 %)
k_{s1}	[kN/mm]	Side 1 (active and |passive|)	125.9 (8.2 %)	341.4 (18.3 %)	54.2 (25.6 %)
k_{s2}	[kN/mm]	Side 2 (active and |passive|)	131.6 (7.9 %)	303.7 (2.9 %)	38.9 (17.7 %)
k_{s1s2}	[kN/mm]	Side 1 and 2 (active and |passive|)	128.3 (6.5 %)	319.1 (7.2 %)	44.9 (19.1 %)
G_{mean}	[MPa]	Side 1 and 2 (active and |passive|)	526.6 (6.5 %)	561.5 (7.2 %)	100.5 (19.1 %)



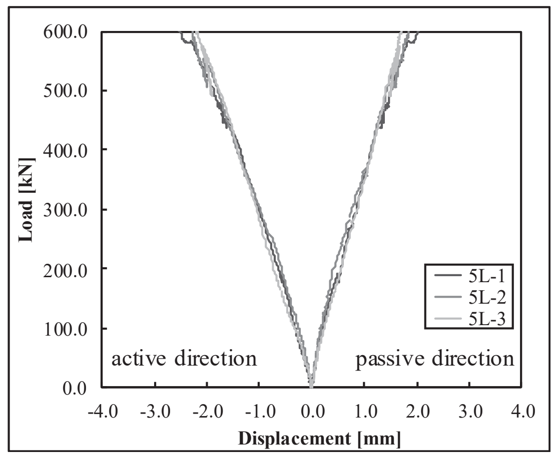


Figure 6: Mean values in active and passive direction in load-displacement diagrams, left: 3-layer CLT, right: 5-layer CLT

4.3 MECHANICALLY DIAGONAL LAMINATED TIMBER

The stiffness values for MLT are also presented in Table 2. The values of the individual test specimens display a considerable degree of spread, see Figure 7, presumably due to the varying board widths and material properties. Noteworthy is the absolute difference of 25.9 kN/mm between the stiffness in passive and active directions. The stiffnesses of sides 1 and 2 also deviate from each other.

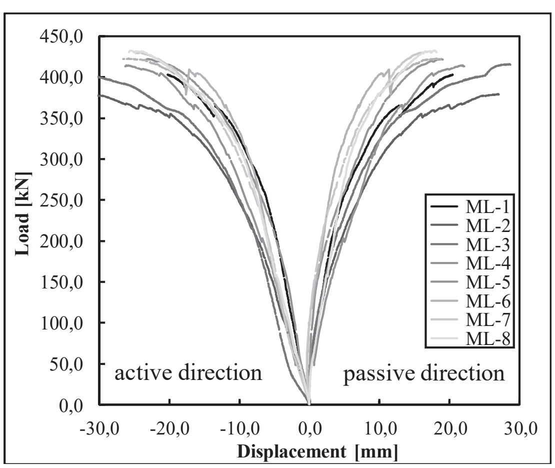


Figure 7: Load-displacement diagram of MLT specimen with mean values in active and passive direction

The asymmetrical layup is the cause of this phenomenon. The MLT elements generally are characterised by a highly ductile load-bearing behaviour. The mechanical connection via aluminium nails consistently resulted in torsion failure. With increasing loads, the large deformation caused the upright diagonal layer to get locked between the frame legs. The acting pressure led to buckling of the layer and the entire element.

The shear modulus G_{mean}, calculated in the elastic range, is 100.5 MPa.

5 – DISCUSSION

5.1 CROSS LAMINATED TIMBER

The values of the shear modulus of CLT in the literature depend on the chosen test configuration and layup of the test specimen, see Table 3. In comparison, the measured mean shear modulus of the 3- and 5-layer CLT with 527 MPa and 562 MPa are in the range and therefore seem plausible.

However, the results show that the measured stiffnesses in the two directions and on the two sides are different. It follows that there is no pure shear field over the measured area. The difference of about 19 % between the active and passive direction is much higher than the almost perfect alignment achieved by Turesson et al. [7] using bolts. This may be due to imperfections in the load transfer through the notches or an oversized measurement area. On the other hand, the difference is not as significant as in diagonal compression tests [7, 13]. Further research is needed to determine whether a correction factor needs to

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Table 3: Comparison of shear modulus of 3- and 5-layer CLT with values from literature

G_{mean}		Test Configuration	3-layer [MPa]	5-layer [MPa]
Andreolli et al.	[13]	Diagonal Compression Test	-	545-549
Dujic et al.	[15]	Diagonal Compression Test	500	-
Turesson et al.	[7]	Diagonal Compression Test	549	656
Brandner et al.	[4]	Diaphragm Shear Test	490-590	460-550
Bjornfot et al.	[6]	Picture Frame Test	-	553
Turesson et al.	[7]	Picture Frame Test	418	466
Fochler et al.	This study	Picture Frame Test	527	562

be introduced.

Due to the failure of the notches and the resulting change in the test configuration, only the stiffness values determined up to that point can be used. More precise analyses of the final state of stress due to the changed application of force are necessary for statements regarding shear strength.

However, the net shear failure that has finally occurred is typical for non-edge glued CLT. It also shows that this picture frame test can cause an in-plane shear failure.

5.2 MECHANICALLY DIAGONAL LAMINATED TIMBER

The torsional failure of the MLT is also in line with expectations. It shows that MLT elements with diagonal layers can be tested within this test configuration. However, the measured values for stiffness and strength are unreliable, as no comparative values are available in the literature. Due to too many unknown variables and possible system effects from the diagonal layers, no valid conclusions can be drawn. Further experiments with variations of DLT and MLT are therefore needed.

6 – CONCLUSIONS

This study addresses the development of a modified picture frame test setup to determine the in-plane shear behaviour of various kinds of timber based materials. The designed configuration incorporates notches for load transfer along the edges to accommodate CLT, DLT and MLT planes. The specific geometry of the notches was determined and implemented. The test specimen should be processed by machine to ensure a tight fit and load transfer. Tests carried out on 3- and 5-layer CLT panels showed that the resulting shear field and shear modulus were consistent with those reported in the literature. Despite the shear failure of the notches, in-plane shear failure was successfully achieved. Overall, this proves that this type of picture frame test setup can be used to determine the in-plane shear behaviour of CLT. With additional specimens tested, it has been demonstrated that MLT and DLT can also be tested using this method, which previously required complex, full-scale testing. However, further validation is required before this modified test can be widely adopted. Planned future tests include comparisons with the established EN 16351 method and investigations like the influence of edge board width. Finite element modelling will be used to carry out detailed parameter studies and assess the shear field's quality.

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