A new test configuration to determine the slip modulus of connections between crosswise bonded boards

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Summary

A new test method is presented that allows for a more accurate determination of the slip modulus of crossing areas between orthogonally bonded boards compared to the methods used so far. The slip moduli obtained by the new method are compared to the values evaluated from bending tests with CLT beams and from tests with crossing areas subjected to unidirectional shear stresses and the agreement is found to be good.

1. Introduction

In CLT members loaded in plane the connections between orthogonally bonded boards are subject to shear stresses. While the glued connections themselves can be considered rigid, the wood matrix near the adhesive joint undergoes deformation which is large enough to affect the global deformation behaviour of CLT members significantly. The overall shear deformation of CLT members loaded in plane therefore can be considered as being composed of two parts, i.e. the shear deformation of boards and the shear deformation of crossing areas. While the former part depends on the shear modulus of the boards, the latter part can be described by means of a slip modulus K of crossing areas which indicates the stiffness of connections with crosswise bonded boards. Blaß and Flaig [1] proposed an analytical approach for the calculation of an effective shear modulus of CLT members loaded in plane that takes account of both components of shear deformation. But while the shear modulus of boards is given in standards, only little information is available on the deformation behaviour of connections with orthogonally bonded boards that are subjected to torsional or unidirectional shear stresses. Blaß and Görlacher [1] and Jöbstl et al. [2] performed tests to determine the torsional stiffness of crossing areas but the values obtained from either test series differ considerably. Partly, the disparity can be explained by the

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different methods that were used in testing: The results presented by Jöbstl et al. include shear distortions within the entire thickness of the two bonded boards whereas deformations due to compressive stresses perpendicular to the grain are contained in the values given by Blaß and Görlacher who applied the torsional moment by means of a clamping. Wallner [3] performed tests with crossing areas subjected to unidirectional shear stresses. But again the measured displacements comprised deformation not originating from the glued connections and due to CLT untypical loading. Therefore, in all of the earlier studies the stiffness of crossing areas is underestimated by far and a test method to determine the slip modulus of crossing areas without any influence of test setup and board thickness is needed.

2. Effective in-plane shear modulus of CLT members

In Figure 1 the two components of shear deformation occurring in CLT members loaded in plane are illustrated. The distortion γ_S in the left picture is due to shear strain in the boards and equals the shear deformation in solid materials (In CLT members with edge-glued lamellae this is the only component of shear deformation). The distortion γ_{CA} shown in the right figure results from mutual displacements and rotations in the crossing areas that occur in CLT members in which the edges of lamellae are unglued. The latter can be calculated in dependence of the slip modulus K of crossing areas and the shear stresses acting in crossing areas.

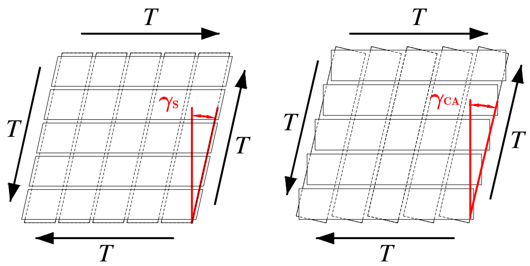


Figure 1: The two components of shear deformation in CLT members loaded in-plane

By assuming a linear stress strain relation a fictive shear modulus $G_{eff,CA}$ can be derived that represents the proportion of shear deformation resulting from the crossing areas. For rectangular cross sections Eq. 1 is obtained where b is the board width, n_{CA} is the number of crossing areas in thickness direction and m is the number of lamellae in direction of the member height [1], [4].

$$G_{eff,CA} = \frac{K \cdot b^2}{5} \cdot \frac{n_{CA}}{t_{gross}} \cdot \frac{m^2}{(m^2+1)} \qquad \text{Eq. 1}$$

The superposition of shear deformation in the lamellae and the crossing areas yields an effective shear modulus $G_{eff,CLT}$ of CLT members that includes both components.

$$G_{eff,CLT} = \left(\frac{1}{G_{lam}} + \frac{1}{G_{eff,CA}} \right)^{-1} \qquad \text{Eq. 2}$$

3. Experimental study

3.1 Single crossing areas - new test configuration

3.1.1 Material

To determine the torsional stiffness of individual crossing areas 24 cross shaped specimens were cut from two orthogonally arranged layers of CLT slabs. Around the crossing areas to be tested gaps with a width of 25 mm were cut in transversal layers to allow for mutual rotations of the two central boards and for the mounting of measuring devices. Otherwise, transversal layers were not removed to strengthen areas of supports and load application and to reduce the eccentricity in thickness direction. The CLT slabs were bonded with a melamine based adhesive which is the most common type of adhesive in CLT manufacturing. However, to investigate a possible influence of the adhesive type ten additional specimens with identical dimensions were assembled in the laboratory using one-component polyurethane adhesive. All specimens consisted of Norway spruce (picea albies) with a moisture content of 10±1%.

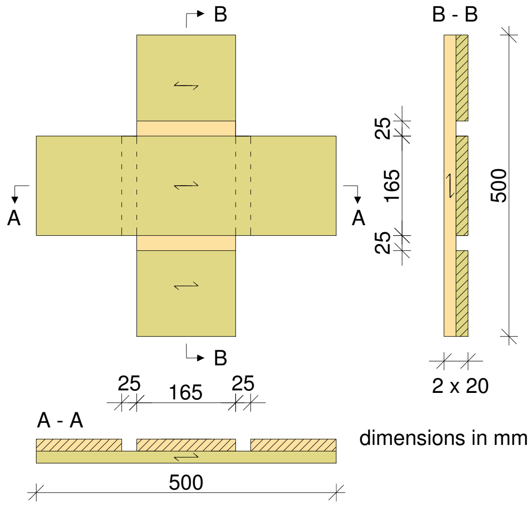


Figure 2: Dimensions of test specimens

3.1.2 Test setup

A steel frame consisting of two crosswise arranged steel bars as illustrated in Figure 3 was used to apply a torsional moment to the central crossing area of the specimens. The vertical bar of the frame was fixed to the testing machine at its lower end whereas the horizontal arm was connected to the former with only one bolt in the center of the crossing area. The bolted connection allowed for free rotation of the horizontal bar but prevented horizontal and vertical displacements relative to the center of the crossing area. At the ends of both bars steel plates were welded at right angles to form supports for the vertical board and to apply loads at the ends of the horizontal

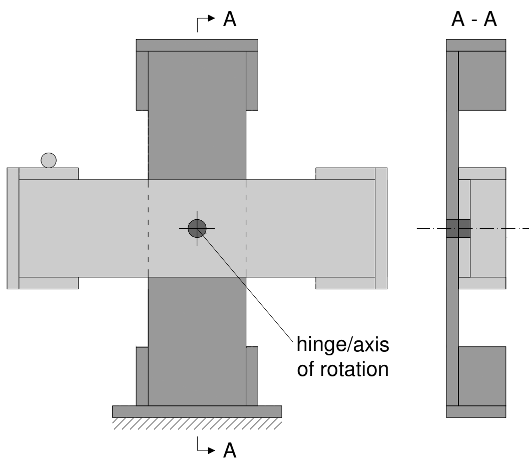


Figure 3: Hinged steel frame

board. To enforce a rotation about the centre of the crossing area a single load was applied on one side of the horizontal bar. In the corners of the crossing areas four displacement transducers were arranged in such way that the mutual rotation between the boards could be measured immediately in the plane of the bonded board surfaces. In addition the rotation of the horizontal board was measured in the centre of the crossing area.

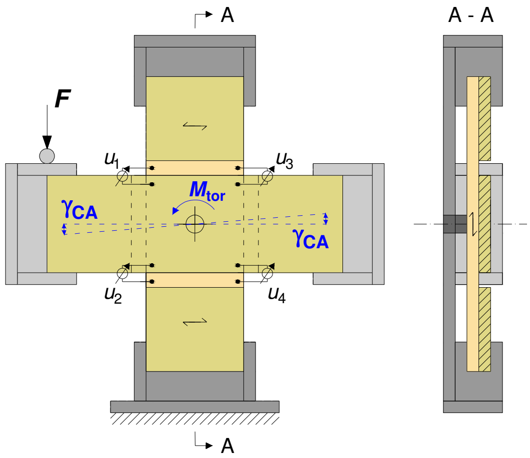


Figure 4: Test setup

3.1.3 Results

The slip moduli K were calculated from the load rotation curves between 10% and 40% of the ultimate load according Eq. 3 where γ_{CA} is the mutual rotation between the two bonded boards that was calculated from the mean values of the four measured displacements and I_p ist the polar moment of inertia of the crossing area.

$$K_{CA} = \frac{\Delta M_{01-04}}{\Delta \gamma_{01-04} \cdot I_p} \qquad \text{Eq. 3}$$

The values obtained for the specimens bonded with the melamine based adhesive range between 6.3 N/mm³ and 10.3 N/mm³ with a mean of 8.3 N/mm³. The test series with polyurethane adhesive resulted in slightly lower slip moduli with a mean of 7.1 N/mm³ and individual values ranging between 5.3 N/mm³ and 8.9 N/mm³. The rotations measured in the centre of the crossing area were rather inaccurate since the measuring devices on the horizontal board had to be fixed to the outer surface averted from the bond line. Consequently, these values were not used to evaluate slip moduli. The torsional shear strength of the crossing areas was calculated according Eq. 4 where M_u is the torsional moment calculated with the ultimate load and b is the side length of the quadratic crossing area. The results of all tests are given in Table 1 and Table 2. The compilation also contains the densities of the two boards of each connection.

$$\tau_{tor} = \frac{M_u}{I_p} \cdot \frac{b}{2} \qquad \text{Eq. 4}$$

Table 1: Test results - melamine adhesive

No.	ρ_1 in kg/m³	ρ_2 in kg/m³	τ_{tor} in N/mm²	K_{CA} in N/mm³
1	581	509	2.71	7.00
2	361	518	2.28	9.40
3	347	395	2.25	7.55
4	535	422	2.49	9.18
5	459	414	3.03	7.77
6	441	447	3.18	8.99
7	369	451	2.93	10.3
8	436	352	2.67	6.42
9	479	482	3.46	8.15
10	419	386	2.79	7.42
11	510	459	3.01	9.16
12	430	412	3.28	8.63
13	451	357	3.50	6.50
14	353	387	2.97	9.77
15	468	418	2.10	9.18
16	382	470	2.04	6.54
17	462	355	3.65	8.04
18	483	409	3.20	7.68
19	383	464	3.19	10.1
20	416	435	2.87	7.52
21	354	380	2.33	7.09
22	386	369	2.69	6.33
23	466	417	2.38	8.95
24	423	473	2.15	9.24
mean	433	424	2.80	8.26

Table 2: Test results - polyurethane adhesive

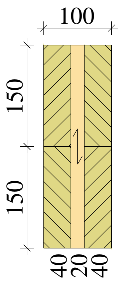
No.	ρ_1 in kg/m³	ρ_2 in kg/m³	τ_{tor} in N/mm²	K_{CA} in N/mm³
1	417	420	3.22	8.33
2	387	393	3.44	5.87
3	510	549	4.07	8.91
4	433	436	3.47	8.80
5	415	426	2.88	6.35
6	360	382	3.15	6.29
7	345	344	2.96	5.98
8	557	553	3.87	8.92
9	360	394	3.59	5.28
10	375	398	3.61	5.85
mean	416	430	3.43	7.06

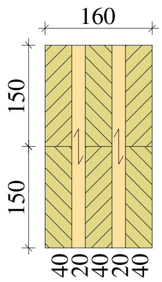
3.1 Comparative tests

3.1.1 Bending tests

In four-point bending tests with CLT beams the global deflection in the middle of the span and the local deflection between the two single loads were measured [4]. The differences between local and global MOEs evaluated from the respective deflections were used to estimate the effective shear moduli of the CLT beams. From these the slip moduli K_{CA} were calculated using Eq. 1 and Eq. 2 and a shear modulus of the lamellae of 690 N/mm².

Table 3: Stiffness properties evaluated from bending tests





series 2-2	$E_{lok,gross}$	$E_{glob,gross}$ in N/mm²	$G_{eff,CLT}$	K_{CA} in N/mm³	series 3-2	$E_{lok,gross}$	$E_{glob,gross}$ in N/mm²	$G_{eff,CLT}$	K_{CA} in N/mm³
	12160	10880	300	7.35		9255	8685	409	11.1
	13024	11528	291	6.99		9240	8558	336	7.27
	13752	11744	233	4.89		10568	9495	271	4.96
	10400	9376	276	6.39		9165	8573	384	9.64
	10952	9416	195	3.76		9983	9353	430	12.6
	7680	7216	346	9.64		7433	6893	275	5.08
	8120	7424	251	5.47		7613	7163	351	7.95
	7872	7016	187	3.56		6983	6630	381	9.43
	8048	7560	361	10.5		7200	6863	424	12.2
	8184	7448	240	5.11					
mean			268	6.36				362	8.92

3.1.2 Diagonal compressive tests

Compressive tests according to a method proposed by Kreuzinger and Sieder [5] have been performed to determine the in-plane shear strength and stiffness of three-layered CLT slabs. Rectangular specimens were cut at an angle of 45° to the direction of boards and a compressive load acting in plane direction was applied at the narrow side of the specimens. The test setup is shown in Figure 5. From the vertical shortening u_y that was measured on both surfaces of the specimens the MOE at an angle of 45° to the materials principle axes was evaluated. Assuming the MOEs of the lamellae with values of 11000 N/mm² parallel to the grain and 370 N/mm² perpendicular to the grain, respectively, the shear modulus $G_{xy,M}$ of the specimens, which is equal to the effective shear modulus $G_{eff,CLT}$, was calculated by transformation into the material coordinate system (x_M,y_M). The slip moduli of the crossing areas were calculated as described in section 3.1.1.

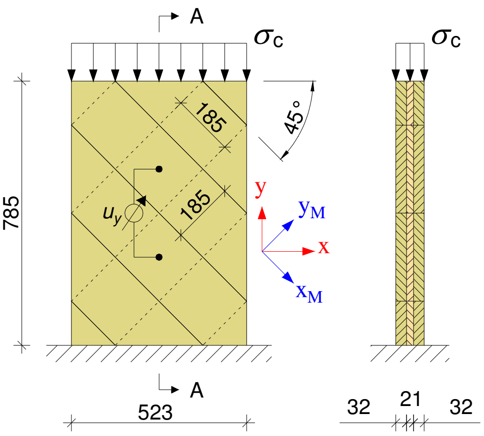


Figure 5: Setup of diagonal compressive tests

Table 4: Results of diagonal compressive tests

No.	E_v in N/mm²	$G_{eff,CLT}$ in N/mm²	K_{CA} in N/mm³
C1	1493	449	10.0
C2	1809	569	25.2
C3	1532	464	11.0
C4	1618	495	13.6
C5	1692	523	16.8
mean	1629	500	15.3

4. Discussion and conclusions

The presented test method allows for the measurement of rotations immediately in the plane of the bonded board surfaces and the experimental determination of the slip modulus of crossing areas without any influence of the test setup and the board thickness. The obtained values are suitable to calculate the proportion of shear deformation of CLT members resulting from stresses in the crossing areas. This allows for the distinction between shear deformation in the crossing areas and shear deformation within the boards which is useful in the calculation of the overall shear deformation of CLT members by means of an effective shear modulus, which depends on the layup and the board width and therefore is not a constant value.

The torsional stiffness of crossing areas that was determined by means of the new test method are roughly two times as high as found in earlier studies. The slip moduli of the specimens bonded with the polyurethane adhesive were slightly smaller than for the melamine bonded, however, the influence of the adhesive type was found to be rather small. In Table 5 the slip moduli obtained from different test series with individual crossing areas are given together with the slip moduli evaluated from beam tests and from diagonal compressive tests. The comparison of the values shows that there is good agreement between the slip moduli determined by the new test method and both, the values evaluated from bending tests and the values presented by Blaß and Flaig (2013) for crossing areas subjected to unidirectional shear stresses. The slip moduli that were evaluated from diagonal compressive tests, in contrast, are even higher than the former. The higher values are mostly due to unintended gluing between the edges of adjacent lamellae that was observed in the tested specimens but may also result from friction to some extent.

Table 5:Slip moduli of crossing areas obtained by different test methods

Author	Test method	Slip modulus in *N/mm³*
Blaß and Görlacher(2002)	single crossing areas (torsion)	4.87
Jöbstl (2004)	single crossing areas (torsion)	3.45
Wallner (2004)	single crossing areas (unidirectional)	4.26
Flaig and Meyer (MUF)	single crossing areas (torsion)	8.28
Flaig and Meyer (PU)	single crossing areas (torsion)	7.06
Flaig (2013)	four point bending tests with CLT beams	7.57
Blaß and Flaig (2013)	two crossing areas (unidirectional)	7.67
Flaig and Meyer	diagonal compressive tests with CLT slabs	15.3

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