COMPRESSIVE STRENGTH AND STIFFNESS OF END GRAIN CONTACT JOINTS IN GLULAM AND CLT

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KEYWORDS

timber, glulam, CLT, end grain contact joints, strength reduction, slip modulus

1 INTRODUCTION

The design of timber members loaded in compression parallel to grain, e.g. columns, walls and bracing elements, is usually governed by buckling, lateral torsional buckling or a combination of both. However, in members with small slenderness ratio or with local reduction of the cross-sectional area, strength may govern the design. Current design codes therefore require the verification of both, stability and strength, the lat-ter usually in consideration of cross-sectional reductions.

If load is transferred via contact between two end grain surfaces, e.g. in stacked col-umns of multi-storey buildings or pre-stressed CLT bracing walls, yet another kind of failure may occur, which is not covered by design codes so far.

In compressive tests with continuous timber members, failure is usually observed around defects, e.g. knots or fibre deviations, or in areas with reduced cross section. In tests with end contact joints, in contrast, failure is observed almost exclusively directly in or close to the joint. Compressive failure in timber members is usually characterised by compressive wrinkles and local buckling of split-off fibre bundles. In members with end grain contact joints a similar failure can be observed, but here, in addition, deep imprints of the latewood parts of the annual rings of the counterpart occur in the con-tact surfaces of the jointed members (Fig 1).

Figure 1: *Typical compression failure at end grain contact joint in CLT: joint after failure (top), contact surfaces with mutual imprints of annual rings (below).*

2 EXPERIMENTAL WORK

2.1 Test series

Four different test series were performed to determine the strength and the stiffness of end grain contact joints in glulam and CLT, the latter also with different moisture contents and with steel plates in the contact

Table 1: Overview of test series

material	contact joint	steel plate	service class	number of specimens	layup/layer thickness in mm (cross layers underlined)	length in mm	width in mm	depth in mm
CLT (REF)	no	no	1	15	40-20-40-40-20-40	1200	600	200
CLT	yes	no	1	15	40-20-40-40-20-40	2 x 600	600	200
CLT	yes	no	1 a)	13	40-20-40-40-20-40	2 x 600	600	200
CLT	yes	yes	1 a)	15	40-20-40-40-20-40	2 x 600	600	200
GL (REF)	no	no	1	16	20-40-20	480	100	80
GL	yes	no	1	16	20-40-20	2 x 240	100	80

a) The moisture content of the test specimens corresponded to service class 1. In addition, the contact surfaces were wetted for 30 minutes before the tests to simulate possible rainfall or other precipitation during transport and erection.

joints. In addition, to determine the de-crease of the mechanical properties resulting from the joints, two reference test se-ries (REF), with CLT and glulam specimens without contact joint, were performed. The strength class of all CLT specimens was C24, the glulam specimens complied with strength class GL24h. Table 1 gives an overview of the test series.

2.2 Test setups

For all test series with CLT specimens a test setup according to EN 408 was chosen, i.e. the length of specimens was 6-times the depth and the deformation uglob was meas-ured within a length of 4-times the depth. In test series with end grain contact joint, in addition, the local deformation uloc near the joint was measured within a length of 60 mm. Figure 2 shows the principle test setup used in test series with CLT specimens.

For the test series with glulam specimens the principle test setup also was chosen ac-cording to EN 408. However, the deformation was not measured as required in the standard within a length of 4-times the depth but within a length of 100 mm. Figure 3 shows the test setup used in glulam test series.

3 TEST RESULTS

3.1 Test data and evaluation

For every specimen the applied load F, the global deformation uglob, and in test series with contact joint also the local deformation uloc were measured with a frequency of 1 Hz. The load deformation curves generated from the test data are shown in the fol-lowing sections. The moisture content and the density were also determined for each specimen or for each part of specimen in test series with contact joint. From the test data the compressive strength, the modulus of elasticity and the slip modulus of the joint were calculated and compared to determine the impact of the joints on the load bearing capacity and the stiffness of the tested members.

The compressive strength was calculated as the ratio

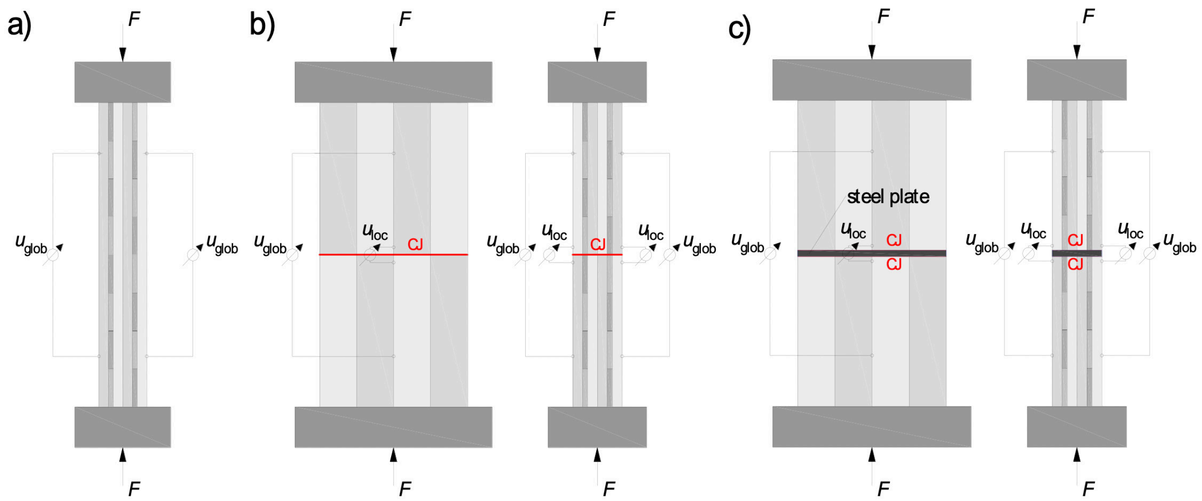

Figure 2: *Test setup used for CLT specimens without contact joint (a), with contact joint (b) and with steel plate in the contact joint (c).*

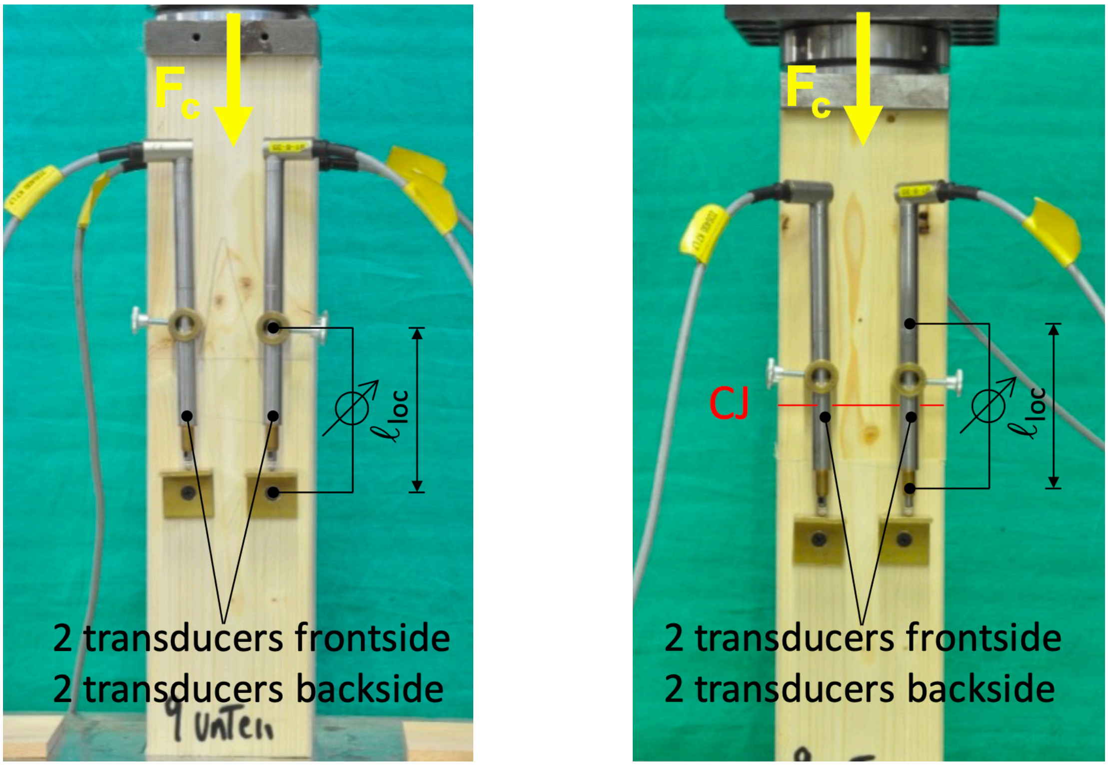

Figure 3: *Test setup used for glulam specimens to determine the MOE in the joint (left) and to determine the strength and stiffness of the end grain contact joint (right) by Schmidt and Blass. The tests were carried out at KIT and partially by A. Berti / Italy.*

between the ultimate load and the cross-sectional area of lamellae with grain direction parallel to the applied load, i.e. for glulam the full cross section and for CLT the net cross section of longitudinal layers.

$$f_{c,0,GL} = \frac{F_{max}}{A} \quad \text{and} \quad f_{c,0,CLT} = \frac{F_{max}}{A_{net,long}} \tag{1}$$

For the reference series without end grain contact joint the MOE was determined according EN 408 from the load-deformation curves of the global deformation u_{glob} between 10% and 40% of the ultimate load using a linear regression.

$$E_{c,0,eff,GL} = \frac{\Delta F}{\Delta u} \cdot \frac{\ell_{glob}}{A} \quad \text{and} \quad E_{c,0,eff,CLT} = \frac{\Delta F}{\Delta u} \cdot \frac{\ell_{glob}}{A_{net,long}} \tag{2}$$

In test series with contact joint two different methods were used to determine MOE and slip modulus of the joint:

i) In test series with CLT the MOE and the slip modulus were evaluated from the deformation measured during main compressive tests

ii) In test series with glulam the MOE of each (part of a) specimen was determined separately in a pre-test

3.1.1 Evaluation of test series with CLT

For the evaluation the MOE and the slip modulus of the mechanical model shown in Figure 4 was used.

It was further assumed, that each of the measured deformations, u_{glob} and u_{loc}, consists of two parts, one resulting from strain in the timber and the other from local indentations in the vicinity of the joint. With the axial stiffness of the timber parts EA and the stiffness of the end grain contact joint K_{CJ}, the measured deformations u_{glob} and u_{loc} can be described by the expressions given in eq. (3).

$$\begin{bmatrix} \Delta u_{glob} = \dfrac{\Delta F \cdot \ell_{glob}}{EA} + \dfrac{\Delta F}{K_{CJ}} \\ \Delta u_{loc} = \dfrac{\Delta F \cdot \ell_{loc}}{EA} + \dfrac{\Delta F}{K_{CJ}} \end{bmatrix} \tag{3}$$

Using the substitution $m = \frac{\Delta F}{\Delta u}$ and solving eq. (3) for the MOE of the members E and the slip modulus of the end grain contact joint K_{CJ} the expressions given in eq. (4) is obtained:

$$\begin{bmatrix} E_{c,0} = \dfrac{\ell_{glob} - \ell_{loc}}{A_{net,long} \cdot \left(1/m_{glob} - 1/m_{loc}\right)} \\ K_{CJ} = \dfrac{\ell_{glob} - \ell_{loc}}{\ell_{glob} \cdot 1/m_{loc} - \ell_{loc} \cdot 1/m_{glob}} \end{bmatrix} \tag{4}$$

To determine slip moduli independently of the member size the values calculated from eq. (4) were divided by the cross sectional area of the test specimens, i.e. for CLT the net cross section of longitudinal layers.

$$k_{CJ} = K_{CJ} \,/\, A_{net,long} \tag{5}$$

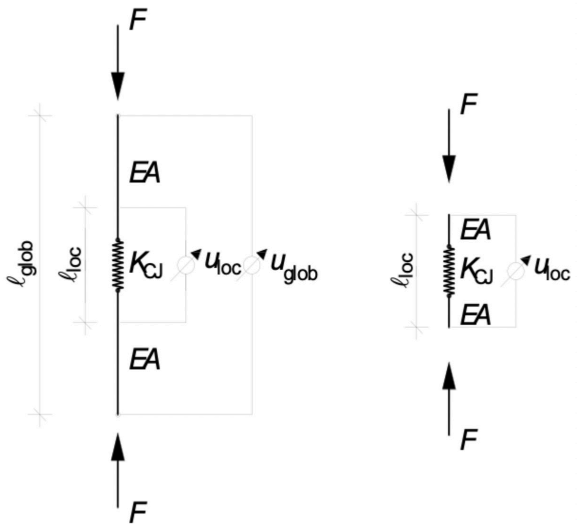

Figure 4: *Mechanical model used for the evaluation of CLT tests (left) and glulam test (right).*

3.1.2 Evaluation of test series with glulam

A slightly different method was used to determine the stiffness of the contact joints in glulam, see Figure 5. At first, all specimens were loaded up to 40 % of the estimated failure load in a pre-test series and the modulus of elasticity within the length ℓ_{loc} was evaluated from the obtained data according to eq. (6).

$$E_{0,c} = m \cdot \frac{\ell_{loc}}{A} \quad \text{with } m = \frac{\Delta F}{\Delta u} \tag{6}$$

In a second step, half of the specimens were loaded until failure without implementing end grain contact joints (REF series). The second half of the specimens were cut in the middle, and one part was turned by 180° around its longitudinal axis to ensure different orientations of the annual rings in opposite contact surfaces. Then, the two parts were put on top of each other and loaded until failure.

For specimens with end grain contact joint the MOE determined in advance was used to calculate the joint stiffness K_{CJ} from the local deformation u_{loc} measured in the main tests. The expression given in eq. (7) for the local deformation can be derived from the model shown in figure 4 (right). After few transformations and simplifications, the expression in eq. (8) is obtained for the stiffness of the end grain contact joint K_{CJ}.

$$\Delta u_{loc} = \frac{\Delta F \cdot \ell_{loc}}{EA} + \frac{\Delta F}{K_{CJ}} \tag{7}$$

$$K_{CJ} = \left(\frac{\Delta u}{\Delta F} - \frac{\ell_{loc}}{EA} \right)^{-1} \tag{8}$$

As for CLT, the slip moduli calculated from eq. (8) were divided by the cross sectional area of the test specimens to obtain values independent of the member size.

$$k_{CJ} = K_{CJ} \ / \ A \tag{9}$$

In the following sections the load deformation curves, the density, the moisture content and the stiffness parameters $E_{0,c}$ and k_{CJ} for all test series are given in detail.

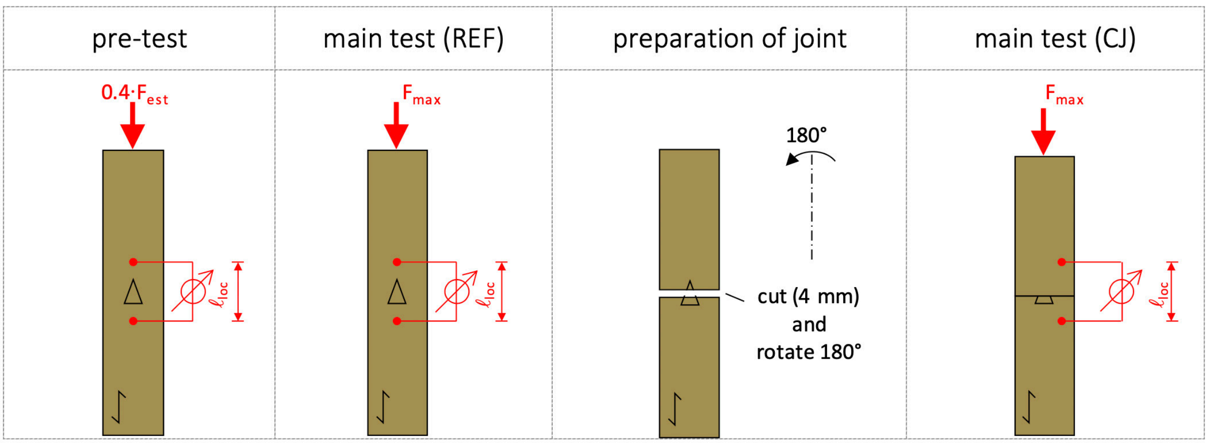

Figure 5: *Test setup used for glulam specimens by Schmidt and Blass.*

3.1.3 Test results for CLT

Table 2: Test results for CLT specimens without contact joint

specimen No.	ρ_1 in kg/m³	ρ_2 in kg/m³	MC_1 in %	MC_2 in %	$f_{c,0,net}$ in N/mm²	$E_{c,0,eff}$ in N/mm²
1	454	-	10.9	-	38.2	12387
2	467	-	10.7	-	36.5	12328
3	438	-	11.0	-	38.3	12377
4	451	-	10.9	-	36.8	11519
5	446	-	10.9	-	36.4	11713
6	442	-	10.0	-	41.0	13064
7	429	-	10.0	-	38.0	11371
8	427	-	10.0	-	37.6	12116
9	465	-	10.5	-	38.0	11917
10	442	-	10.7	-	37.9	11566
11	432	-	10.4	-	36.3	11403
12	449	-	10.7	-	38.5	11820
13	444	-	10.2	-	38.0	11530
14	480	-	10.1	-	39.6	12561
15	436	-	10.3	-	36.0	12564
MIN	427		10.0		36.0	11371
MEAN	447		10.5		37.8	12016
MAX	480		11.0		41.0	13064
5th percentile					35.2	

Table 3: Test results for CLT specimens with contact joint

specimen No.	ρ_1 in kg/m³	ρ_2 in kg/m³	MC_1 in %	MC_2 in %	$f_{c,0}$ in N/mm²	$E_{c,0}$ in N/mm²	$E_{c,0,eff}$ in N/mm²	k_{CJ} in N/mm³
1	430	447	10.1	10.7	35.5	11262	8126	139
2	443	442	10.8	10.4	34.7	10135	7583	198
3	418	444	10.9	10.7	34.1	11193	8003	123
4	432	428	10.9	10.2	32.8	11273	7923	106
5	419	438	10.9	10.8	33.9	10644	7636	121
6	436	455	10.8	10.4	33.6	11035	8257	216
7	434	444	10.9	11.1	33.6	10816	8017	183
8	456	458	11.2	10.7	36.3	12234	8671	126
9	448	462	11.2	10.9	37.0	12014	8911	205
10	457	462	11.2	11.0	35.5	11604	8374	141
11	458	457	11.2	10.8	36.2	12424	8968	151
12	459	447	11.2	11.0	36.4	11260	8268	167
13	435	464	10.2	11.0	33.8	11185	7978	120
14	439	461	10.5	11.0	34.6	11222	8256	171
15	420	454	10.5	11.1	32.6	10027	7292	133
MIN	418	428	10.1	10.2	32.6	10027	7292	106
MEAN	439	451	10.8	10.8	34.7	11222	8151	153
MAX	459	464	11.2	11.1	37.0	12424	8968	216
5^{th} percentile					32.0			

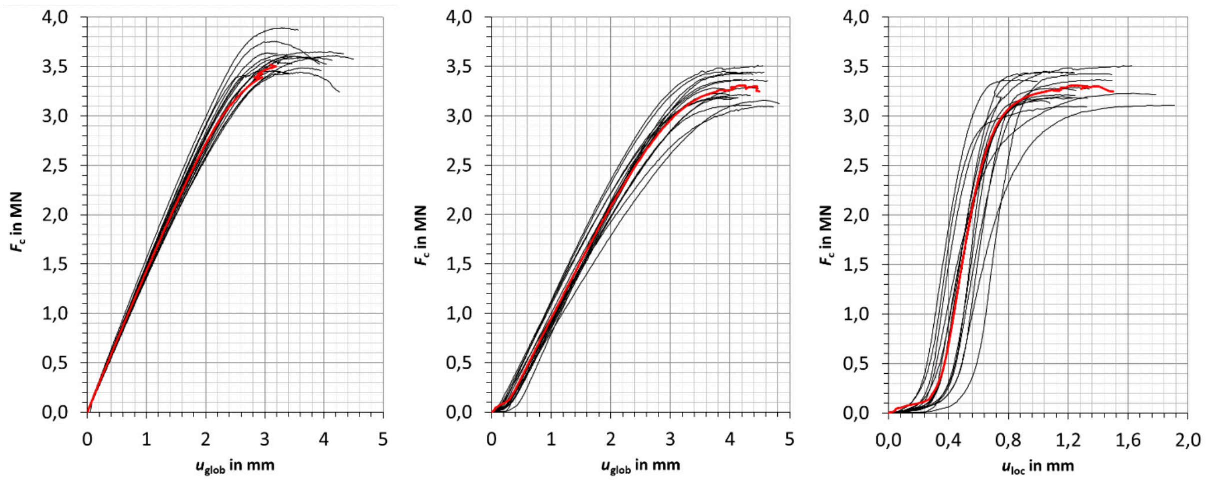

Figure 6: *Load-deformation curves for CLT specimens. Left: reference series without contact joint. Middle and right: series with contact joint. Red curves represent mean values.*

3.1.4 Test results for glulam

Table 4: Test results for glulam specimens with and without contact joint

Reference series without contact joint				Test series with contact joint				
specimen no.	ρ in kg/m³	$f_{c,0}$ in N/mm²	$E_{c,0}$ in N/mm²	specimen no.	ρ in kg/m³	$f_{c,0}$ in N/mm²	$E_{c,0}$ in N/mm²	k_{CJ} in N/mm³
1	489	38.5	14520	1	482	32.0	14120	363
2	488	40.8	13490	2	484	33.2	11350	261
3	439	34.5	12050	3	488	33.8	16660	362
4	451	31.1	11580	4	456	33.2	9220	275
5	502	39.2	11140	5	494	34.4	9850	266
6	494	40.1	14300	6	425	32.2	10340	252
7	443	36.5	10670	7	499	29.6	13170	330
8	507	37.3	13980	8	506	31.1	13520	307
9	483	35.5	13990	9	443	32.6	10260	259
10	429	34.7	11900	10	449	33.9	11270	274
11	504	35.6	11830	11	432	35.6	10900	370
12	419	35.5	11290	12	503	41.2	16130	365
13	459	37.0	14240	13	496	40.8	13300	283
14	497	38.3	14330	14	412	32.8	11310	263
15	517	35.9	12110	15	508	40.2	14330	482
16	470	37.0	14330	16	459	36.2	12110	375
MIN	419	31.1	10670	MIN	412	29.6	9220	252
MEAN	474	36.7	12859	MEAN	471	34.5	12365	318
MAX	517	40.8	15200	MAX	508	41.2	16660	482
5th percentile		32.2		5th percentile		28.5		

The mean moisture content was 11.8 % (COV 9.2 %).

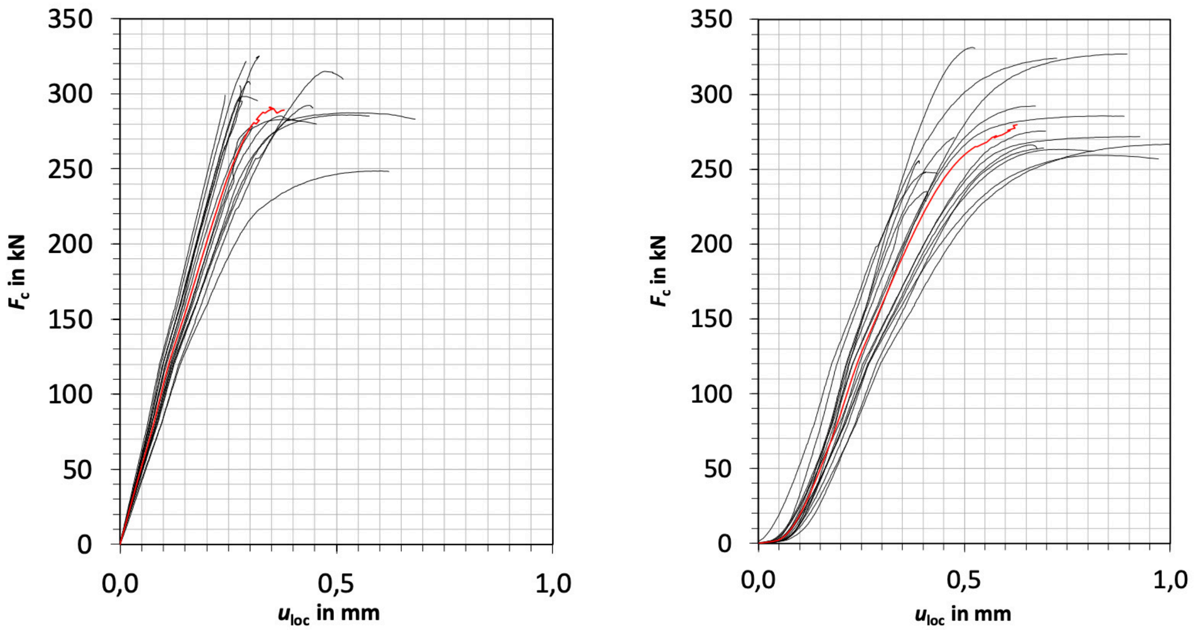

Figure 7: *Load-deformation curves for glulam specimens. Left: reference series without contact joint. Right: series with contact joint. Red curves represent mean values.*

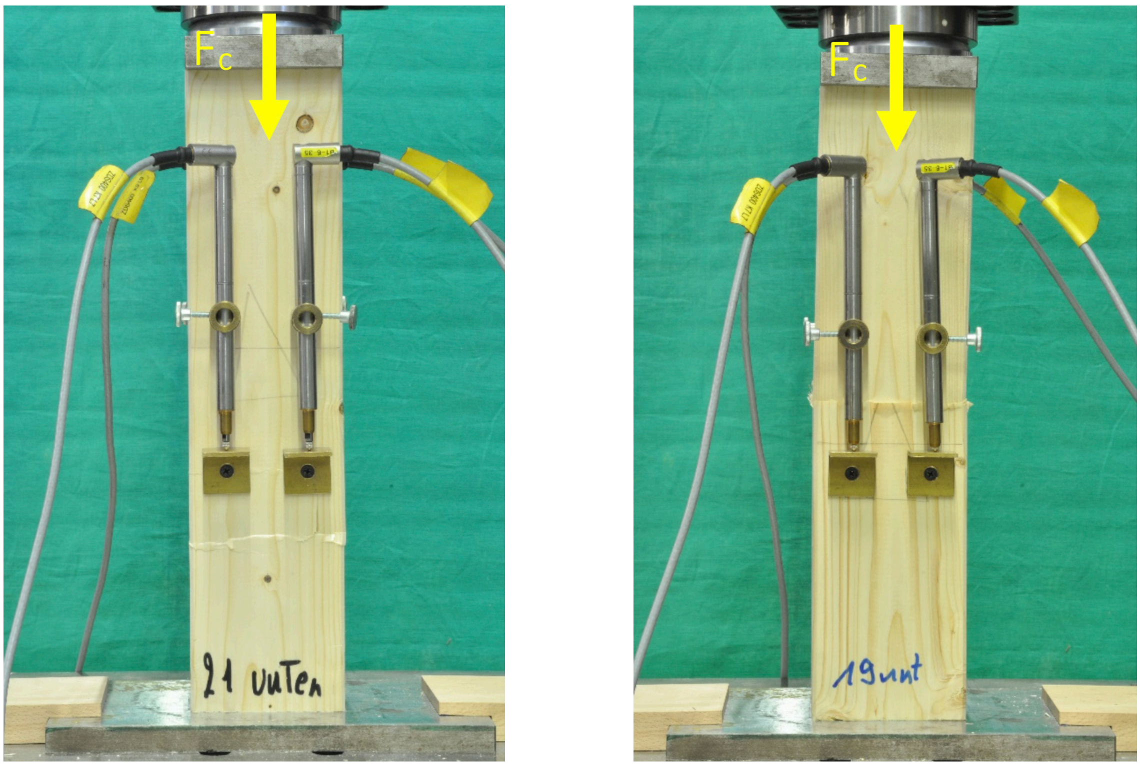

Figure 8: *Glulam specimen after failure. Left: without contact joint. Right: with contact joint.*

3.1.5 Test results for CLT and wetted contact surfaces

Table 5: Test results for CLT specimens with contact joint tested with wetted contact surfaces

specimen no.	ρ in kg/m³	*MC* in %	$f_{c,0}$ in N/mm²	$E_{c,0}$ in N/mm²	k_{CJ} in N/mm³
1	446	12.4	24.8	12300	31.3
2	434	12.7	26.0	9000	38.0
3	467	12.5	26.3	11900	9.26
5	473	12.6	27.8	12900	33.4
6	452	12.8	27.2	11700	37.7
7	460	12.7	25.7	12200	42.9
8	456	12.7	26.3	11500	24.2
9	465	11.7	26.5	13300	30.3
10	447	11.7	26.9	10000	44.4
11	435	7.9	27.5	12000	23.9
12	439	11.1	27.8	11500	41.5
14	441	12.7	27.7	11500	26.5
15	432	12.3	27.3	8850	51.7
MIN	432	7.90	24.8	8850	9.26
MEAN	449	12.0	26.8	11435	33.5
MAX	473	12.8	27.8	13300	51.7
5th percentile			24.9		

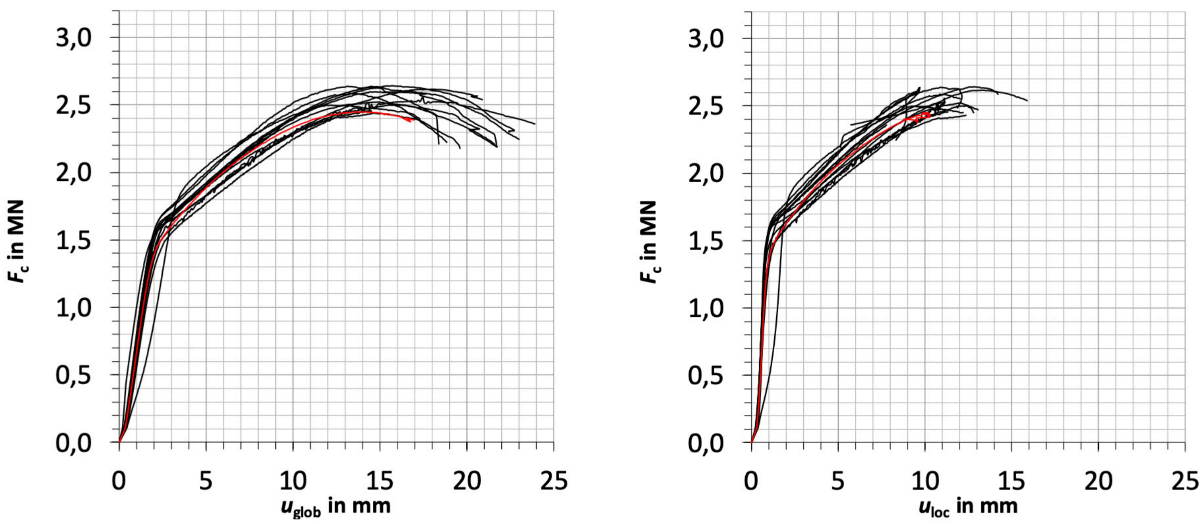

Figure 9: *Load-deformation curves for CLT specimens with contact joints tested with wetted contact surfaces; red curves represent mean values.*

Figure 10: *Typical compression failure at contact joint in CLT specimen: joint after failure (left), contact surfaces with mutual imprints of annual rings (right).*

Table 6: Test results for CLT specimens with contact joint and steel plate tested with wetted contact surfaces

specimen No.	ρ in kg/m³	MC in %	$f_{c,0}$ in N/mm²	$E_{c,0}$ in N/mm²	k_{CJ} in N/mm³
1	433	11.2	29.9	12300	34.1
2	433	12.2	29.0	10900	17.9
3	456	11.5	29.5	11300	32.8
4	463	11.6	28.2	12600	33.0
5	467	12.5	30.9	14600	28.2
6	453	12.8	28.9	12000	33.6
7	456	12.9	30.4	11500	30.8
8	442	12.6	29.5	11400	35.6
9	450	12.8	31.6	12500	39.8
10	453	11.1	30.5	12900	41.4
11	440	11.6	30.4	13300	27.7
12	458	12.4	30.2	17100	29.2
13	458	12.7	32.5	12600	31.2
14	451	12.2	31.8	12300	40.3
15	450	12.8	31.3	10800	37.7
MIN	433	11.1	28.2	10900	17.9
MEAN	451	12.1	30.1	12692	32.0
MAX	467	12.9	32.5	17100	41.4
5th percentile			28.0		

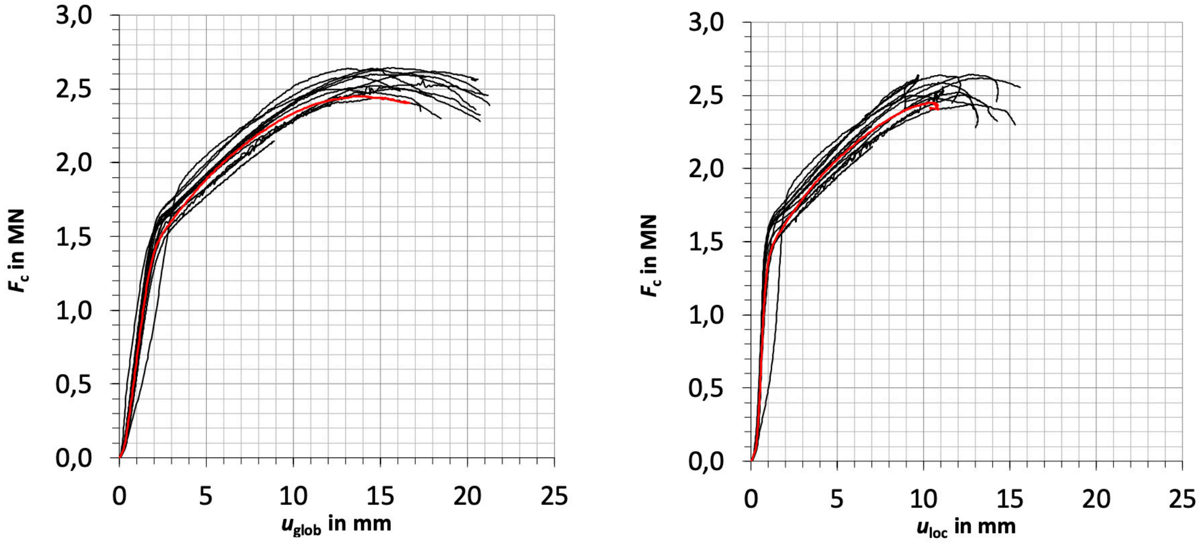

Figure 11: *Load-deformation curves for CLT specimens with steel plate in the contact joint tested with wetted contact surfaces; red curves represent mean values.*

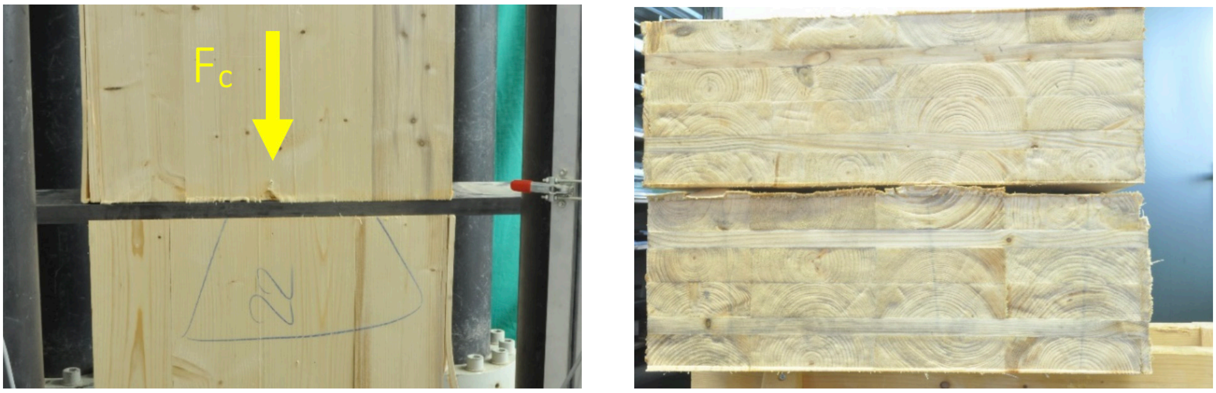

Figure 12: *Typical failure of CLT specimens with steel plate in the contact joint CLT joint after failure.*

4 DISCUSSION AND CONCLUSIONS

In all of the tested specimens, in CLT and glulam and without as well as with wetted surfaces, compressive failure and large deformation were observed close to the contact joint. In a few cases, also locally limited failure was observed at defects apart from the contact joints, e.g. knots or finger joints, but no significant impact on the overall deformation could be observed.

CLT and glulam | (values for glulam in brackets)

For CLT and glulam reductions of the compressive strength resulting from the end grain contact joints of 8.2 % (6.0 %) for the mean values and 9.1 % (11.5 %) for the characteristic values were found. Although, the strength reduction is significant, the reduced values of characteristic strength of 32.0 N/mm² (28.5 N/mm²) is still by far higher than the nominal values of the tested strength classes.

For CLT and glulam the additional deformation resulting from the end grain contact joints is about 1 mm (0.5 mm) under ultimate load and about 0.5 mm (0.2 mm) under the design compressive stress at ultimate limit state which equals approximately 40 % of the ultimate load measured in the tests.

CLT with wetted surfaces | (values for steel plate joints in brackets)

For CLT tested with wetted surfaces reductions of the compressive strength resulting from the end grain contact joints of 29.1 % (20.3 %) for the mean values and 29.3 % (20.5 %) for the characteristic values were found. Although the strength reduction is very significant, the reduced values of characteristic strength of 24.9 N/mm² (28.0 N/mm²) are still higher than the nominal value of the tested strength classes.

However, for CLT with wetted surfaces (simulation of a possible rainfall or other precipitation during transport and erection) the additional deformation resulting from the end grain contact joints is more than 10 mm under ultimate load for both, contact joints without and with steel plate in the contact joint. Under the design compressive stress at ultimate limit state which equals approximately to 40 % of the ultimate load measured in the tests the deformation is still about 1.0 mm.

The test results show, that the deformation resulting from end grain contact joints, including a relatively large joint slip, can reach values that are incompatible with serviceability requirements. This is particularly the case in constructions with several end grain contact joints arranged in a row, e.g. multi-storey buildings where the deformation of the contact joints and elastic and creep deformation of the members can add up to critical values. Moreover, the long-term behaviour of loaded end grain contact joints is currently unknown, and additional creep deformation of end grain contact joints cannot be excluded.

In fact, the influence of moisture content on the compressive strength and the stiffness of end grain contact joints is enormous and by far higher than in continuous members. Therefore, it is crucial to plan and implement appropriate measures to prevent the absorption of moisture during transport and erection especially wetting of end grain surfaces must be avoided by any means.

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