World Conference on Timber Engineering Oslo 2023

BENDING PROPERTIES OF 100 NARROW CLT-BASED BOARDS – STATIC AND DYNAMIC TESTS AND DIC ANALYSIS

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ABSTRACT: Production of CLT-panels typically results in 5-10% cut-offs due to window and door openings. CLT-boards can be made by slicing these cut-offs and finger-jointing them. This paper presents bending properties of 100 narrow CLT-boards (45x95x1800) made from 5-ply CLT panels made of Norway spruce. A limited variation in E-modulus (CV=9%) and bending strength (CV=20%) was found with gross section values not far from typical structural C24-timber. The tests indicate that narrow CLT-boards have sufficient bending properties for being used as structural components, also where the bending capacity is formally utilized. However, the variation was slightly higher than for typical tests on larger CLT-elements (CV=8-16%), probably due to the smaller homogenization effect when fewer sub-parts carry the load. The rolling shear modulus was estimated to be G_r= 65 MPa, which is to be expected due to the distance from the pith of the cross layer boards. The surprisingly high net flatwise bending strength ($f_{m,05}$=49 MPa) can likely be attributed, for the most part, to the reinforcing effect from the cross layers that limit the slope of grain cracking near knots in the longitudinal layers. DIC-tests revealed an indication of a non-plane normal strain distribution over the beam depth in the shear-free zone between the inner loading points. This might lead to an underestimation of the shear-free local E-modulus according to EN 408.

KEYWORDS: CLT, bending strength, E-modulus, rolling shear modulus, strain distribution, DIC-analysis

1 INTRODUCTION

The background of this study is the urge to find smart use of cut-offs from production of Cross Laminated Timber (CLT), see Figure 1. Due to window and door openings, 5-10% of all CLT material is typically chipped up to become biofuel. The idea here is to slice these cut-offs and finger-joint them to CLT-boards with sizes similar to structural timber. It has been verified that this kind of boards can successfully be finger-jointed.

The cross-layers weaken the bending properties compared with solid wood, but give the CLT-boards superior properties when loaded in the perpendicular direction as with horizontal rails in a wall frame. An up to fivefold increase in capacity has been found, see Vessby et al. [1]. However, in this paper the focus is on the bending properties of this kind of narrow CLT-based boards to verify that they have properties that allow for typical handling in the production of timber frame elements. Tests are also warranted in view of applications of the CLT-boards where the bending properties are critical also for formal load-bearing.

It has been shown in many studies that the variation in bending strength is much smaller in CLT, thanks to the fact that many boards carry the load together. One severe defect in an individual is not critical for the strength as neighboring boards carry the load. The coefficient of variation is typically CV=8-16%. Structural timber has a greater variation, especially if the classification is done to only one low grade like C24 and reject: (CV=30-35%). However, most studies on CLT has been done on quite large elements, typically 600 mm wide, which contain several boards. It is not clear how much narrower CLT-boards behave in bending where defects in single boards potentially are more critical for the overall behavior.

In the standardization work in Europe, the size limitations for the applicability of the CLT-standard for small sizes are discussed [2]. This study may contribute to the discussion about such limits. Furthermore, few studies have been done on the in-plane bending strength, especially with small sizes. One of few studies of small size CLT is the one reported by Flaig and Blaß. (2014). [3]. They studied the in-plane bending properties of smaller specimens down to 100x150 mm^2 with a focus on the lamination (system) effect. Their results are encouraging and indicated a substantial positive effect of the cross layers on the in-plane bending strength. However, the narrow CLT-boards focused on here are much smaller and only 45 mm deep for the in-plane bending mode (flatwise in this case).

The objective of this study was to investigate not only the edgewise properties but also the flatwise bending properties as the latter is of importance for practical handling at the construction site and/or at the pre-fabrication factory.

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https://doi.org/10.52202/069179-0089

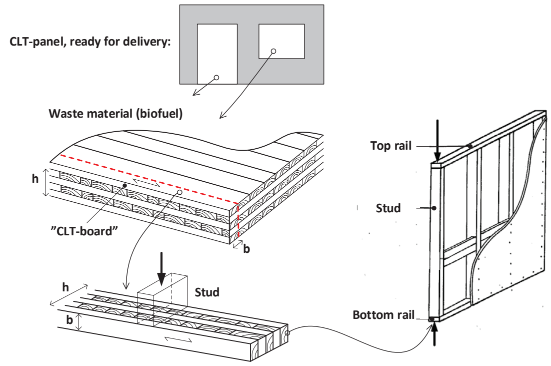

Figure 1: *Illustration of one of many possible uses of the cut-offs from CLT panels — horizontal rails (CLT-board).*

2 MATERIAL AND METHODS

2.1 MATERIAL

The material for the study came from the normal CLT-production at the Stora Enso mill in Gruvön, Sweden. A so called C5s panel with the intended use as a wall element was chosen. This 100 mm thick 5-ply CLT consisted of 20 mm thick layers of Norway spruce boards, strength graded as a single grade to T15. In this case it is comparable to C24, which for Nordic material gives a grading yield of about 99%. The boards were side-glued.
A total of 100 CLT-boards (slices) were produced and planed to the desired standard size (45x95x1800 mm^3) according to Figure 2. The thickness of the layers were: 17.25+20.3+20.3+20.3+17.25 mm resulting in an actual width of 95.4 mm. The boards were in this case cut from one full-size CLT-panel and not from cut-offs. Therefore, there was no need for finger-jointing of board parts from cut-offs. However, it should be noted that the individual boards in the CLT-panel were finger-jointed as usual. The layers were made of 100 mm wide, flat sawn side boards with an average distance from the board center to the pith of approximately 120 mm, see Figure 2. It can also be noted that some longitudinal layers were laminated and contained material from two different side-glued boards. Approximately 80% of the boards had one or more laminated layers.
The average moisture content of the boards was 9.4% and all reported elastic properties were adjusted to the reference moisture content 12%.

Figure 2: *Flatwise view and section of CLT-board where layer 3 and 5 is laminated (consists of two side-glued boards).*

2.2 STATIC TESTS AND DIC MEASUREMENTS

The CLT-boards were tested to determine the edgewise (50 pcs) and flatwise (50 pcs) static bending properties following the EN 408 standard [4]. One deviation was that the flatwise tests were done using the same test set-up as for the edgewise test with a span of 18 times the width (1710 mm), see Figure 3. Unfortunately, the measurement of the local E-modulus between the loading points using a yoke on the tension edge did not give reliable results and is not reported here. The global E-modulus E_{gl} is based on the overall mid-span deflection and the value presented here is not corrected for shear deformations, which are considerable due to the weak cross layers. Properties for the gross and net section were calculated. In the latter case the transverse E-modulus of the cross layers was assumed to be zero, E_{90}=0 MPa. The net E-modulus, without shear deformation influence, was calculated from the global value using the gamma method [5], assuming E_{90}=0 MPa and a rolling shear modulus of G_{90}=65 GPa based on dynamic test analysis.
Strain and displacement data from a Digital Image Correlation (DIC) system was gathered for 5 edgewise boards for the area between the loading points, see Figure 3.

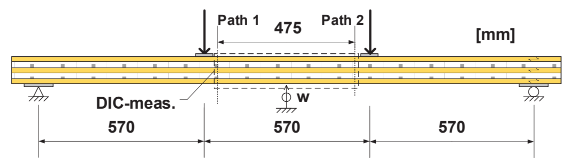

Figure 3: *Bending test set-up according to EN 408 [4] and zone for DIC strain measurement.*

2.3 DYNAMIC TESTS

The 50 boards that were tested in edgewise bending were also subjected to dynamic tests whereby the specimens were suspended in springs to simulate free-free boundary conditions, see Figure 4. Based on geometry, density and resonance frequencies for different vibration modes, E-moduli and shear moduli were determined. The first 3-4 modes of vibrations were analyzed for axial ($E_{d,ax}$), flatwise and edgewise bending ($E_{d,bf}$ + $E_{d,be}$) and torsion ($G_{d,t}$). For the bending vibrations, evaluation was made using beam theory according to both Euler-Bernoulli (Eu) and Timoshenko (Ti). In the latter case the influence of shear deformations and rotatory inertia is taken into account and the approximate solution suggested by Goens [6] was used. See also Hearmon [7] and Perstorper [8] for details on the evaluation of dynamic elastic properties. Since knowledge of the shear modulus G and the ratio E/G is needed for the evaluation, an iterative procedure was used for each board individually until the E-moduli for the first 3 modes of bending vibration coincided as much as possible. This shear-free E-modulus is denoted $E_{d,bf,Ti}$ and $E_{d,be,Ti}$ for flatwise and edgewise bending. As a result of the iteration, a gross shear modulus associated with bending was determined ($G_{d,be}$).

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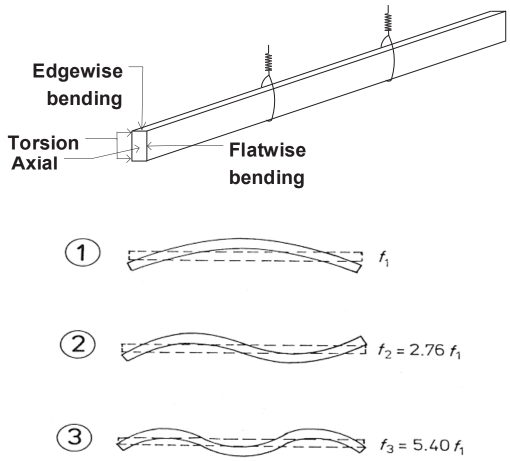

Figure 4: *Dynamic test set-up with indication of excitation directions and accelerometer positions. Visualisation of the mode shape of the first three bending modes.*

A shear mode was observed in the axial tests, for which the outermost layers slide on the weak cross layers, see Figure 5. This vibration mode is governed by the shear stiffness of the cross layers and an attempt was made to establish a model that allowed for an estimation of the rolling shear modulus G_r. In this simplified SDOF-model, the outer layer was modelled as a mass with infinite stiffness and the cross layer below as a shear spring with zero mass.

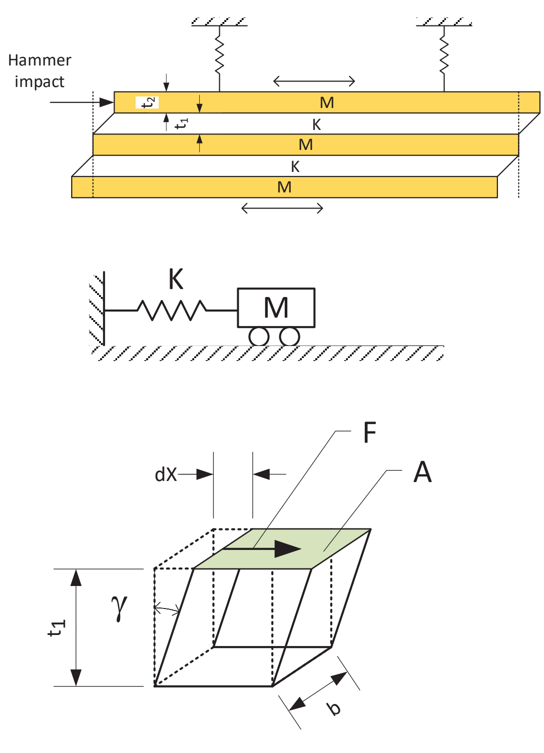

Figure 5: *Shear mode model.*

$$K = \frac{G \cdot A}{t_1} \tag{1}$$

$$f = \frac{1}{2\pi} \times \sqrt{\frac{K}{M}} = \frac{1}{2\pi} \times \sqrt{\frac{G}{\rho \cdot t_1 \cdot t_2}} \tag{2}$$

$$G_{d,r,sh} = (f \cdot 2 \cdot \pi)^2 \cdot \rho \cdot t_1 \cdot t_2 \tag{3}$$

The evaluated mode was the one where layer 3 was a node that did not move. The resulting Equation (3) for the rolling shear modulus $G_{d,r,sh}$ included the thickness (t_2) and density (ρ) of the outer layer, the thickness of the transverse layer (t_1) and the resonance frequency f.

3 RESULTS

3.1 STATIC PROPERTIES

3.1.1 Gross section analysis and overall product performance

The results from the static tests are presented in Table 1 for both the net section and the gross section. The reason for presenting the gross values is that it is easier to compare the overall practical performance of the CLT-boards to solid structural timber. In this sense, the CLT-boards had an edgewise and flatwise bending stiffness that were approximately 30% lower than C24 timber. On the other hand, and as expected, the variation was much smaller for the CLT-boards with a coefficient of variation (CV) of only 9% compared to the usual level for C24 of CV=20-25% for the E-modulus, see Figure 6 and Table 1. At the 5%-percentile level the gross stiffness of the CLT-boards was only 12% lower than the nominal level for C24 ($E_{0,05}$=7.4 GPa).

A similar pattern was found for the gross bending strength, where the bending capacity of the CLT-boards were lower on average but with a smaller variation compared with C24, see Table 1 and Figure 7. The gross average capacity was about 30% (edgewise) and 15% (flatwise) lower for the CLT-boards compared to typical values for single grade C24 ($f_{m,avg}$=45 MPa). The coefficient of variation was 22% and 19% for edgewise and flatwise capacity compared to the typical 30-35% for C24. Thanks to the limited variation, the 5%-percentile value for the gross bending capacity was only 16% lower for the edgewise tests, compared with the nominal value for C24 ($f_{m,05}$=24 MPa). For the gross flatwise bending capacity, the 5%-percentile was actually 19% higher than the C24-value.

In summary, one can conclude that the narrow CLT-boards have gross average bending properties that are not so far from typical structural timber (15-30% lower than C24). Thanks to the limited property variation, the gross 5%-percentile values of the CLT-boards are almost on a par with solid timber. The tests indicate that narrow CLT-boards have sufficient bending properties for being used as structural components, not only as rails but also for situations where the bending capacity is formally utilized.

https://doi.org/10.52202/069179-0089

Table 1: Results from static bending test and physical properties representing the gross and net section. Average values and standard deviation within brackets. Density and E-modulus adjusted to the reference moisture content 12%. The 5%-percentiles were determined using ranking.

Property		Edgewise	Flatwise
Basic data			
Number	n	50	50
Thickness	T (mm)	45 (0.2)	44.8 (0.2)
Width	W (mm)	95.4 (0.1)	95.3 (0.2)
Moisture content	u (%)	9.4 (0.4)	9.4 (0.4)
Density	ρ (kg/m^3)	487 (14)	483 (21)
Gross section			
Global E-modulus (shear infl.)	E_{gl} (GPa)	7.54 (0.70)	7.81 (0.73)
Global E-modulus 5%-perc.	$E_{gl,05}$ (GPa)	6.53	6.77
Bending strength	f_m (MPa)	32.2 (7.0)	38.3 (7.2)
Bending strength, 5%-perc.	$f_{m,05}$ (MPa)	20.2	28.6
Net section assuming E_{90}=0 and G_{90}=65 MPa			
Estim. net E-modulus	E_{net} (GPa)	12.2 (1.13)	13.6 (1.27)
Estim. net E-modulus 5%-perc.	$E_{net,05}$ (GPa)	10.6	11.8
Bending strength	$f_{m,net}$ (MPa)	42.9 (9.3)	66.7 (12.5)
Bending strength, 5%-perc.	$f_{m,net,05}$ (MPa)	27.0	49.1

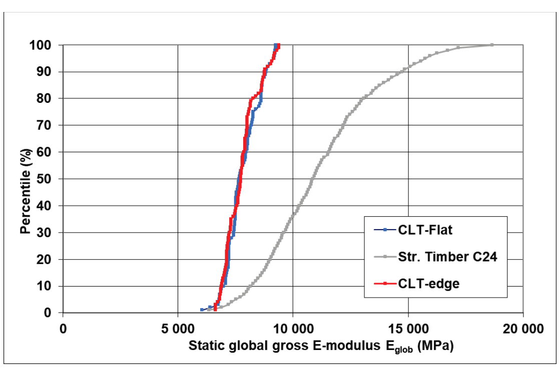

Figure 6: Variation in edgewise and flatwise gross global E-modulus and comparison with typical Nordic structural timber (C24).

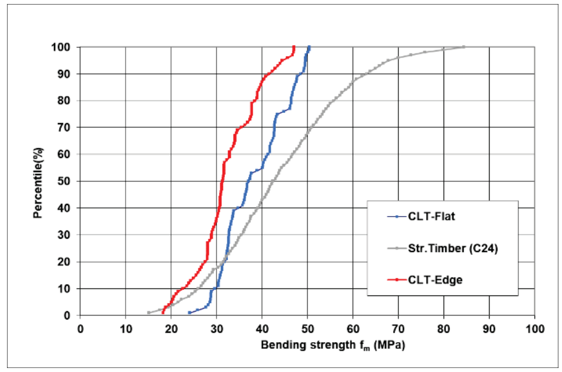

Figure 7: Variation in edgewise and flatwise gross bending strength and comparison with typical Nordic structural timber (C24).

3.1.2 Detailed evaluation and net section analysis

The net section properties presented here are based on an assumption that the E-modulus of the cross layers is zero (E_{90}=0). Furthermore, the effective rolling shear modulus of the cross layers is assumed to be G_r= 65 MPa, based on the dynamic tests, see below (section 3.2).

Based on the edgewise global E-modulus, and using the gamma method [5], the net local E-modulus is calculated to be $E_{net,be}$=12.2 GPa, which is higher than the nominal level of C24 of 11 GPa.

The corresponding net E-modulus for the flatwise tests was much higher: $E_{net,bf}$=13.6 GPa, indicating that the material in these boards might have been of a higher structural quality, despite the fact that the boards for the edgewise and flatwise tests were produced at the same time and came from the same batch. The higher net bending strength of the flatwise tests supports this idea, but the almost equal density does not, see Table 1.

However, side boards cut far from the pith as here has been found to have higher E-modulus and strength in many studies, e.g. Oscarsson et al. [9]

One might argue that a too high rolling shear modulus was assumed for the edgewise gamma evaluation, but it would require a value of G_r=44 MPa to get the edgewise net E-modulus $E_{net,be}$ to 13.6 GPa, which is not likely.

A third possible explanation would be a systematically higher E-modulus of the middle lamella (#3) compared to the outer lamellas (#1 and #5). The dynamic tests of the edgewise boards indicate such a tendency, since the edgewise net E-modulus $E_{d,be,Ti,net}$=12.9 was lower than the flatwise $E_{d,bf,Ti,net}$=13.5 MPa and axial E-modulus $E_{d,ax,net}$=13.8 MPa, see Table 3.

A fourth possible explanation would be if there is a lamination effect that is enhancing the E-modulus of the flatwise tests in another way compared with the edgewise direction. It can be noted that the 36 boards with laminated layers had a higher flatwise E-modulus than the 14 boards without laminations: $E_{net,bf}$ = 13.9 GPa vs 12.6 GPa, see Figure 11. For edgewise tests the effect was smaller: $E_{net,be}$ = 12.2 for the 37 boards with lamination vs. $E_{net,be}$ = 11.8 GPa for the 13 boards without laminations. This might indicate that there is a lamination effect for the E-modulus that possibly work differently in flatwise loading (in-plane) compared with edgewise loading (out-of-plane).

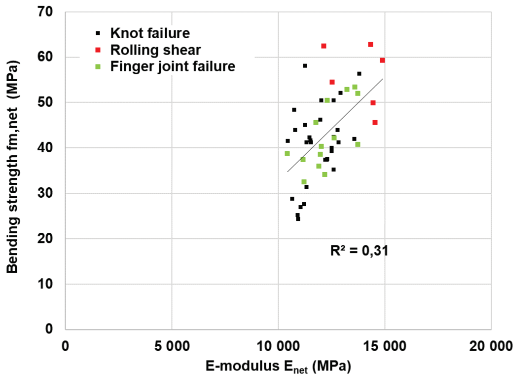

Figure 8: *Correlation between net static edgewise global E-modulus and net bending strength and indication of boards which capacity was limited by rolling shear failure.*

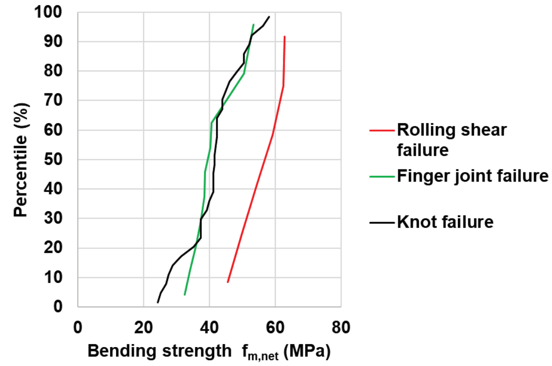

Figure 9: *Percentile plot of net edgewise bending strength for different failure modes.*

Figure 10a: *Examples of failure modes in edgewise bending. Rolling shear (top), knot in tension zone (mid), finger joint in tension zone (bottom).*

Most boards tested on edge, failed in bending due to knots or finger joints at the tension (predominantly) or compression edge, see Table 2 and Figure 8. However, six boards showed a rolling shear failure outside the loading points. This is quite common for bending tests of CLT with a span of 18 times the beam depth but does not influence the 5%-percentile value. These boards had a higher average failure load and E-modulus compared with the boards that failed in bending, see Figure 8 and Table 2.

The estimated shear stress in the cross layers at failure for the six boards was on average 1.36 MPa, with a range from 1.11 – 1.53 MPa. This is slightly lower than the rolling shear strength reported for Norway spruce by Ehrhart et al [10] but close to the tabled value for C24 for which the characteristic 5%-percentile value is $f_{v,90,k}$=1.1 MPa. It should be noted that there were drying cracks in the cross layers prior to testing, which may have had an influence, see Figure 2. Such cracks are common in CLT when the moisture content in service is lower than it was at the time of production.

It can be noted that the boards with finger joint failure had an average bending strength and E-modulus on a par with boards that failed due to knots. At the lower end of the strength distribution, there were only knot failures. Finger joints seem not to introduce weaknesses that lower the bending strength distribution, see Figure 9.

Table 2: *E-modulus and bending strength for different failure modes for edgewise tests, net section: Rolling shear failure in cross layers and tension/compression failure in outer layers due to knots or finger joints.*

Failure mode	No.	E-modulus	Bending strength
		E_{net} (GPa)	$f_{m,net}$ (MPa)
Rolling shear	6	13.8	55.7
Finger joint (tension or compression)	12	12.2	41.6
Knot (tension or compression)	32	11.9	40.6
All	50	12.2	42.9

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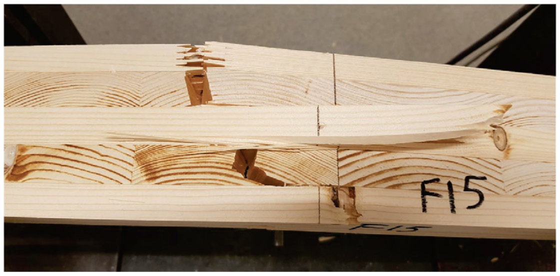

Figure 10b: *Example of bending failure in flatwise bending.*

The net edgewise bending strength was on average $f_{m,net}$=42.9 MPa, which is close to the typical value for Nordic Norway spruce graded to C24 (single grade). The lower variation thanks to the homogenization in CLT led to a 5%-percentile value of $f_{m,05,net}$ = 27 MPa which exceeds the nominal C24-value by 12%, see Table 1. This indicates a lamination effect of 12%, which is stronger than expected for these narrow boards.

However, it shall be noted that 80% of the boards had one or more laminated layers, see Figure 2. The boards without any laminated layers had a 5%-percentile edgewise bending strength of 24 MPa, indicating no difference to the board strength, see Figure 11.

For the flatwise tests, the net bending strength was surprisingly high with an average of $f_{m,net}$=66.7 MPa; almost 50% above the typical value for C24. The 5%-percentile of $f_{m,05,net}$=49.1 MPa was more than double the value for C24.

The net E-modulus was also high (13.6 GPa) for the flatwise tests, supporting the idea of a quality difference. However, it is not likely that a quality difference is the sole reason, since an average E-modulus of 13.6 GPa corresponds to an average bending strength of approximately 50 MPa and a 5%-percentile of 30 MPa, using a database for Nordic Norway spruce from approval tests of grading machines.

Other contributing factors might be that the middle layer (#3) were stronger than the outer layers (#1 and #5), see discussion above for the E-modulus. This would lead to a higher flatwise net strength than edgewise.

An important influencing factor is likely the lamination effect (homogenization). It is plausible that the lamination effect is stronger for flatwise loading, where three layers carry the load in parallel, see Figure CC. In edgewise loading a single defect in the outer lamellas is more critical for these narrow boards.

In the study by Flaig and Blass [3] the lamination effect for in-plane bending was estimated to 8-9% for a lay-up with 3 longitudinal layers in parallel, which would indicate a 5%-percentile bending strength of a single board to 49.1/1.085=45 MPa.

Furthermore, the same study showed a substantial effect of the cross layers on the bending strength. A 5 mm thin cross layer on the side of a board, tested in edgewise bending, increased the average bending strength by 18% (34.0 vs 40.3 MPa). Based on estimations from a graph in the report, the difference at the 5%-percentile level could be more than 60% (13.4 vs 22.2 MPa). Apparently, the cross layers, with a high cross stiffness, strengthened the weak sections by limiting cracking associated with grain deviations around knots.

If one assumes a cross layer enhancement effect of 50% on the 5%-percentile bending strength, and a lamination effect of 8.5%, the 5%-percentile bending strength of the individual layers would be 30 MPa to fit the strength of the CLT-board. This is in fact close to the strength corresponding to the measured flatwise net E-modulus of 13.6 GPa.

If one or more layers were laminated (two side-glued boards), the bending strength was higher compared to CLT-boards where each layer consisted of only one board, see Figure 2 and 11. Out of the 50 CLT-boards tested edgewise, 13 pcs had no laminations and the corresponding number for the flatwise tests was 14 CLT-boards.

The influence of laminations was more pronounced for the boards tested in flatwise bending compared to the edgewise tests at the median level, but the opposite at the 5%-percentile level.

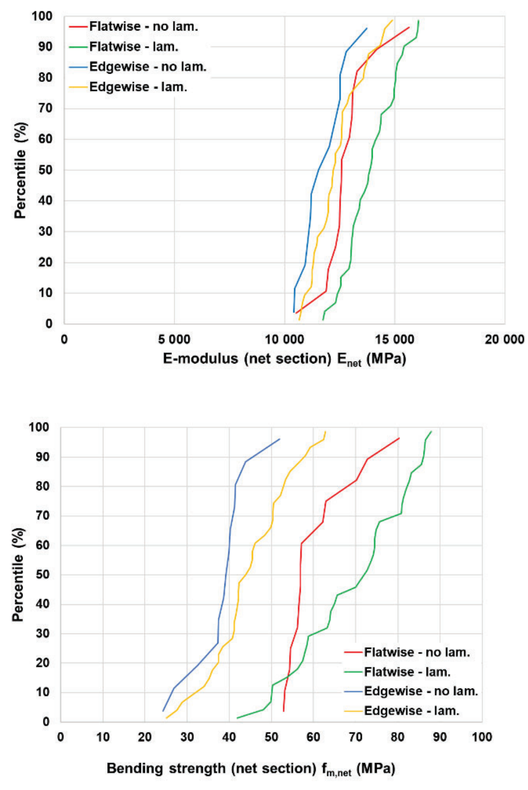

Figure 11: *Percentile plots of net E-modulus and net bending strength for boards that had no laminated layers compared with boards that had one or more layers with lamination (layer with two side-glued boards, see Figure 2).*

3.2 DYNAMIC PROPERTIES AND COMPARISON WITH STATIC RESULTS

A very strong correlation (R^2=0.96) was found between gross dynamic edgewise E-modulus (Euler) $E_{d,be,Eu.gross}$ and gross static global E-modulus $E_{gl,be,gross}$ see Figure 12. Both moduli are influenced by shear deformations more or less in the same way. The dynamic E-modulus was 5,5% higher than the static one, which is found in most studies and is attributed to the large difference in loading speed and the viscoelastic nature of wood.

It can be noted that the shear-free net dynamic E-modulus $E_{d,be,Ti,net}$ = 12.9 GPa coincide very well with the corresponding static E-modulus E_{net} = 12.2 GPa, when taking into account the typical static-dynamic difference. The average shear-free (Timoshenko beam theory) net E-modulus from edgewise bending vibration was $E_{d,be,Ti,net}$ = 12.9 GPa, see Table 3.

In order to match the gross global E-modulus $E_{d,be,Eu,gross}$ =7.96 GPa the rolling shear modulus of the cross layers must be $G_{d,r,gm}$= 69 MPa using the gamma method [5]. Assuming the usual 5.5% difference, the static rolling shear value would be G_r = 65 MPa, which was used when estimating the shear-free static E-modulus in Table 1.

A rolling shear modulus of G_r = 65 MPa is not far from other studies on Norway spruce for boards cut far from the pith: Erhart et al [10] reported an average value of G_r=56 MPa for boards cut 100 mm from the pith.

Görlacher [11] studied the influence of annual ring geometry on the rolling shear modulus of Norway spruce. For the material in the present study, the angle between the tangential ring direction and rolling shear loading was on average 13 degrees, which points at a rolling shear modulus of 60-65 MPa according to the results of Görlacher.

It can be noted that the nominal value for C24 is 50 MPa, which is considered to be a conservative value for typical CLT-boards. However, it is likely a rather good estimate of the constitutive material parameter G_{RT} for Norway spruce to be used in FE-modelling (valid for boards with zero annual ring curvature and purely tangential or radial ring orientation in relation to board geometry).

The analysis of the shear mode, see Figure 5, resulted in a slightly lower rolling shear modulus of $G_{d,r,sh}$ =55 MPa. One reason for the difference is likely that one needs to account for parts of the mass of the cross layers in the model and this would increase the evaluated shear modulus.

The dynamic shear modulus from analysis of three edgewise bending modes was $G_{d,r,be}$ = 132 MPa. This is a weighted gross average over the cross section including influence of both lengthwise and cross layers. A common way of calculating the effective gross shear modulus for a layered material is given in Eq. 4 where V_{cross} and $V_{lengthwise}$ is the volume fractions of the layers; 43% and 57% in this case.

$$\frac{1}{G_{gross}} = \frac{V_{cross}}{G_{cross}} + \frac{V_{lengtwise}}{G_{lengtwise}} \tag{4}$$

Based on the experimental gross shear modulus of $G_{d,r,be}$=132 MPa and by assuming a shear modulus of G_l = 650 MPa for the lengthwise layers, the rolling shear modulus of the cross layers is $G_{d,r}$= 64 MPa, which is quite close to other estimates in this study.

The gross section shear modulus from torsional vibration was $G_{d,t}$ = 266 MPa, which is less than half of the level for solid timber, but not alarming with respect to practical handling at production. It can be noted that in torsion, the cross layers are not subjected to purely rolling shear stresses as in bending. Furthermore, the shear stresses have a more pronounced maximum in the middle layer (#3) in torsion. Both these factors increase the gross section shear modulus for torsion compared to gross shear modulus related to edgewise bending ($G_{d,r,be}$ =132 MPa).

Table 3: *Results from dynamic tests of the 50 boards that were tested in static edgewise bending. Average values and standard deviation within brackets. The stiffness properties are adjusted to the reference moisture content 12%.*

Property and vibration mode		Gross section	Net section
Dynamic E-modulus (GPa)			
Axial	$E_{d,ax}$	7.91 (0.69)	13.8 (1.2)
Flatwise bending, Timoshenko theory	$E_{d,bf,Ti}$	7.77 (0.66)	13.5 (1.1)
Edgewise bending, Euler theory	$E_{d,be,Eu}$	7.96 (0.74)	-
Edgewise bending, Timoshenko theory	$E_{d,be,Ti}$	9.65 (1.1)	12.9 (1.5)
Dynamic shear modulus (MPa)			
Torsion	$G_{d,t}$	266 (13)	-
Edgewise bending Timoshenko theory	$G_{d,r,be}$	132 (8.7)	64
Rolling shear mode Cross layer value	$G_{d,r,sh}$	-	55 (4.4)
Estimate using gamma method, Cross layer est.	$G_{d,r,gm}$	-	69

The dynamic edgewise E-modulus was correlated to the bending strength. Due to the limited property variation of the multi-ply CLT-board, the coefficient of determination was only R^2= 0.38 but the standard error was quite small: SEE=5.6 MPa, see Figure 13. The results indicate a possibility to use dynamic methods to grade the CLT-boards to a bending strength quality comparable to C24. The average E-modulus of C24 will obviously be harder to achieve.

https://doi.org/10.52202/069179-0089

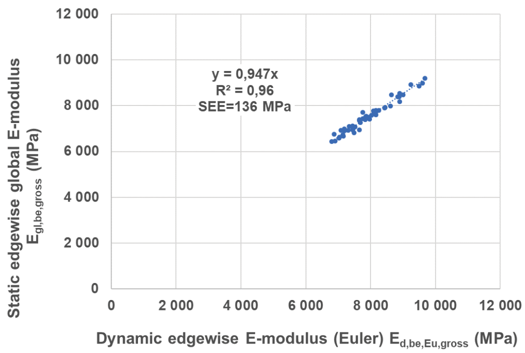

Figure 12: *Correlation between gross dynamic edgewise E-modulus (Euler)* $E_{d,be,Eu,gross}$ *and gross static global edgewise E-modulus* $E_{g,be,gross}$.

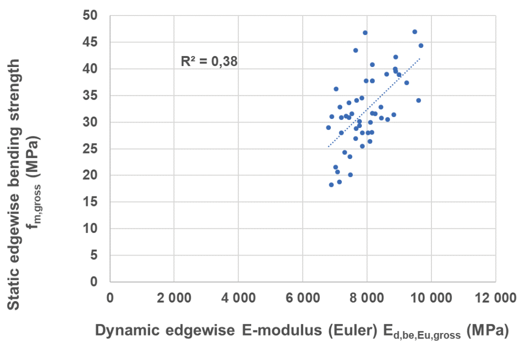

Figure 13: *Correlation between dynamic edgewise E-modulus (Euler)* $E_{d,be,Eu,gross}$ *and bending strength* $f_{m,gross}$ *(gross section values).*

3.3 NON-PLANE STRAIN DISTRIBUTION BETWEEN LOADING POINTS - INFLUENCE ON LOCAL E-MODULUS

A DIC-analysis of 5 CLT-boards was done regarding the bending deflections and normal strains in the area between the inner loading points. The bending deflections at the neutral layer were determined over a length of 475 mm (5h), corresponding to the method of determining the local shear-free E-modulus according to EN408 [4]. A deviation was that the measurements were only done on one of the faces, whereas the standard prescribes measurements on both sides to account for twisting.

The average net local E-modulus $E_{loc,DIC}$ for the 5 boards was 10.8 GPa which is lower than expected. Based on the gross static global E-modulus E_{gl} = 7.42 GPa for these boards, a rolling shear modulus of 65 MPa and using the gamma method, the net local E-modulus should be 11.9 MPa. Furthermore, the gross dynamic edgewise E-modulus using Timoshenko beam theory (shear-free) for the 5 boards was 12.4 GPa, which translates to a comparable static value of 11.8 GPa (5.5% reduction). Thus, both static and dynamic data supports that the static local E-modulus seems to be underestimated by approximately 10%.

A possible reason for the underestimation is that the assumption of plane normal strain in the shear-free zone between the loading points is not valid. In order to check this an analysis was made for a load step of 2.5 kN. The strains were calculated based on the normal deformations (x-direction) in path 1 and 2, at each mm of the beam depth, see Figure 3. The idea was to get a strain distribution that represents an average for the measurement zone and thereby minimize local effects that blur the picture. This revealed a non-plane strain distribution over the beam depth with a steeper strain gradient in layer 1, 3 and 5 compared with the overall inclination, see Figure 14. The degree of deviation from a plane strain varied between the boards, possibly depending on local defects close to the paths chosen. The strain gradient was on average 10% steeper in layer 1,3 and 5 compared to a plane strain situation. It is quite possible that this non-plane strain distribution explains the underestimation of the local shear-free E-modulus. Similar strain distributions have been presented in other studies on models for CLT [12].

Although this part of the beam is not subjected to vertical force causing shear stresses, the beam layers are subjected to the non-plane stress distribution from the beam parts outside the loading points, where the shear-weak cross layers influence the normal stress distribution in the manner seen in Figure 14. The general implication of this is that an evaluation of the local shear free E-modulus according to EN 408 [4] might lead to an underestimation if the beam to be tested has a low shear stiffness, like in this case with very shear-weak cross layers. The increased span-to-depth ratio typically used in CLT-tests to avoid rolling shear failure is beneficial in this respect as the shear deformations are diminished.

However, due to the small amount of boards analysed and the variation, one cannot draw any firm conclusions. Further tests and analysis will be done to see if this effect can be verified.

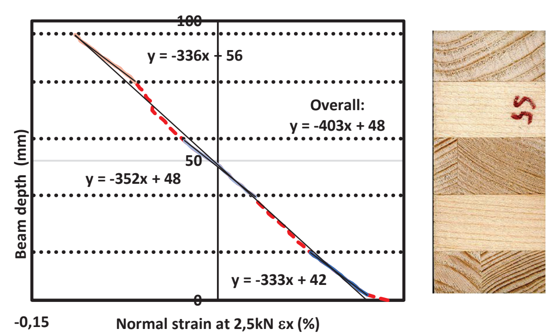

Figure 14: *Non-linear normal strain distribution for board E5, in the shear free portion of the beam between the inner loading points.*

4 CONCLUSIONS

1. The narrow CLT-boards (45x95 mm^2) in this study show gross average bending properties that are not so far from typical structural timber (15-30% lower than C24). Thanks to the limited property variation, the gross 5%-percentile values of the CLT-boards are almost on a par with solid timber. The tests indicate that narrow CLT-boards have sufficient bending properties for being used as structural components, not only with regards to handling but also for situations where the bending capacity is formally utilized.
2. The dominating failure mode in edgewise bending tests was knot failure at the tension edge. The 12 boards that failed at a finger joint had strength on a par with the boards that failed at a knot.
3. Six boards out of 50 exhibited a rolling shear failure. The estimated rolling shear strength was 1.36 MPa, with a range from 1.11 to 1.53 MPa, which is slightly lower than comparable studies on Norway spruce. However, the failure load for these boards were on average 35% higher than the boards that failed in bending.
4. The coefficient of variation for the bending strength was about 20% for both edgewise and flatwise loading, which is in between typical values for CLT (8-16%) and C24 (30-35%, single grade). The small size compared to other CLT-tests seems to reduce the homogenization effect (many sub-parts share the load).
5. The surprisingly high net flatwise bending strength ($f_{m,05}$=49 MPa) can likely, to a high degree, be attributed to the reinforcing effect from the cross layers that limit slope of grain cracking near knots in the longitudinal layers.
6. The rolling shear modulus of the cross layers was estimated to G_r = 65 MPa. This is in line with other studies of flat-sawn Norway spruce side-boards cut far away from the pith.
7. Dynamic E-modulus from edgewise vibration was very well correlated to the global static E-modulus with R^2=0.96. The correlation to bending strength was less strong (R^2=0.38) but with a low standard error (SEE=5.6 MPa).This indicates a possibility for non-destructive testing and grading of CLT-boards to achieve a superior quality for specialty applications.
8. Analysis of the local E-modulus between the loading points of 5 boards based on DIC-measurements indicated a 10% lower level than expected. The analysis also revealed a non-plane normal strain distribution that is likely linked to the low local E-modulus. Further studies are warranted to see if the “shear-free” local E-modulus determined according to EN408 might be underestimated for very shear-weak beams where the non-plane stress distribution outside the loading points have an influence.

ACKNOWLEDGEMENT

The support from several wood construction companies in Sweden, Stora Enso, the innovation program Bioinnovation/Vinnova, and the Knowledge Foundation is gratefully acknowledged.

REFERENCES

[1] J. Vessby, M. Perstorper, M, F. DeMonte, and J. Eriksson.: Structural use of cut-offs from clt-production – three examples that utilize the unique properties. In: World Conference on Timber Engineering, Oslo, 2023

[2] R. Brandner, R. Tomasi, T Moosbrugger, E. Serrano, P. Dietsch (eds.): Properties, Testing and Design of Cross Laminated Timber: A state-of-the-art report by COST Action FP1402/WG2, Shaker Verlag Aachen, 2018.

[3] M. Flaig, and H. Blaß, (2014). Bending strength of cross laminated timber beams loaded in plane. In: World Conference on Timber Engineering, Quebéc, 2014.

[4] EN 408:2010+A1:2012 - Timber structures - Structural timber and glued laminated timber - Determination of some physical and mechanical properties. European Standard.

[5] K. Möhler: Über das Tragverhalten von Biegeträgern und Druckstäben mit zusammengesetzten Querschnitten und nachgiebigen Verbindungsmitteln [About the load bearing capacity of beams in bending and bars in compression with composite cross sections and flexible connections], Habilitation, 1962, TH Karlsruhe (in German).

[6] E. Goens, Determination of Young´s modulus from flexural vibrations (in German). Annalen der Physic 11(6):649-678, 1931.

[7] R. F. S. Hearmon: Theory of the vibration testing of wood. Forest Products Journal, 16(8):29-40, 1966.

[8] M. Perstorper: Dynamic modal tests of timber – evaluation according to the Euler and Timoshenko theories. In: Ninth Int. Symposium on Nondestructive Testing of Wood, 45-54, 1994.

[9] J. Oscarsson, A. Olsson, M. Johansson, B. Enquist and E. Serrano: Strength grading of narrow dimension Norway spruce side boards in the wet state using first axial resonance frequency. International Wood Products Journal, 2(2):108-114.

[10] T. Erhart, R. Brandner, G. Schickhofer, and A. Frangi: Rolling shear properties of some European timber species with focus on cross laminated timber (CLT): test configuration and parameter study. In: Second INTER meeting, Sibenik, Croatia, 2015.

[11] R. Görlacher: A method for determining the rolling shear modulus of timber (Ein Verfahren zur Ermittlung des Rollschubmodulus von Holz), Holz als Roh-und Werkstoff 60:317-322, 2002.

[12] R. Stürzenbecher, K. Hofstetterand J. Eberhardssteiner: Cross laminated timber: a multi-layer, shear compliant plate and its mechanical behaviour. World Conference on Timber Engineering 2010.

https://doi.org/10.52202/069179-0089