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STRUCTURAL USE OF CUT-OFFS FROM CLT-PRODUCTION – THREE EXAMPLES THAT UTILIZE THE UNIQUE PROPERTIES

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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. It is worthwhile from economic and climatic aspects to find applications for such boards as building products with long service life. It is preferred to find uses where the premium transverse properties are utilized. This paper present three novel ideas for re-use of cut-offs from CLT. (a) The re-use as REX laminations in CLT production is a smart concept that minimize waste in an economical way. (b) By using finger-jointed CLT-boards as horizontal rails in timber frame buildings, the problems with over-load and deformations in multi-storey houses are minimized. (c) The capacity of glulam beams to carry concentrated loads is greatly enhanced by integrating CLT-boards as laminations.

KEYWORDS: CLT, REX lamination, perpendicular to grain, re-use, rails, glulam, concentrated load

1. INTRODUCTION

The background to this study is the urge to find smart use for cut-offs from CLT-production, see Figure 1. Due to window and door openings and waste due to non-rectangular shapes of the CLT-panels, 5-10% of all produced CLT material is typically chipped to become biofuel. The idea here is to slice these cut-offs and finger-joint them to CLT-boards with arbitrary length so that these boards have every second layer oriented with the longitudinal direction along the length direction of the board and the other, referred to as "cross-layer", perpendicular to that direction. The cross-layers gives the CLT-boards superior stiffness and strength properties when loaded perpendicular to their length direction since every second layer is then loaded in parallel to the fiber direction, see Figure 1.

It is worthwhile from economic and climatic aspects to find applications for such boards as building products with long service life. It is also favorable to find uses where the premium transverse properties are desired, beneficial and fully utilized.

In this paper, three concepts of re-use of cut-offs are presented and discussed, see Figure 1 (b-d):

a) Re-use as REX lamination in CLT made by Stora Enso
b) CLT-boards as rails in timber frame structures
c) CLT-boards as integrated glulam laminations to enhance capacity for concentrated load

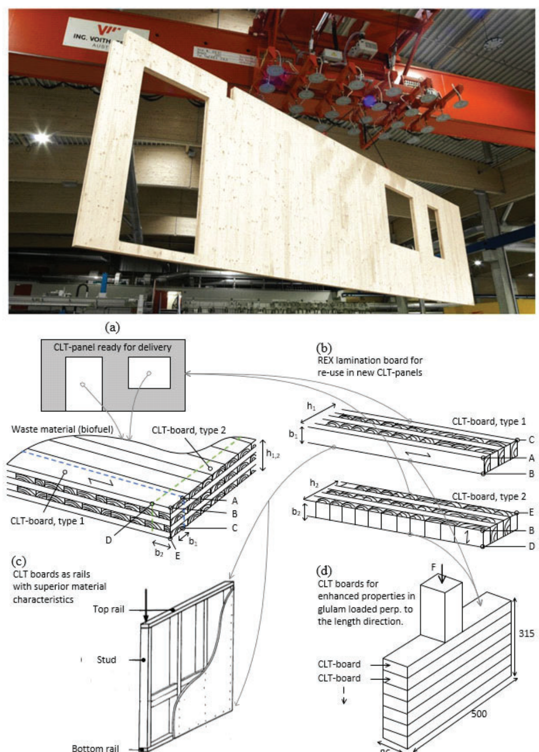

Figure 1: (a) Waste material from CLT-panels sliced into CLT-boards and used for b) re-use in new CLT-panels c) rails in timber structures and d) to enhance performance locally in glulam beams.

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2. RE-USE OF CUT-OFFS AS REX LAMINATION IN CLT

Stora Enso has developed the idea to finger joint slices of the cut-offs and reuse them as transverse layers of floor and roof slabs in CLT production. The properties of this so-called REX laminations are defined in a European Technical Approval (ETA-14/0349) [1], see Figure 2 (a). The effective E-modulus of the REX lamination depends on the proportion of end-grain, which varies between 20-40 %. However, the E-modulus has been set conservatively to E_{REX} = 6 800 MPa for all laminations type REX.

The properties of the longitudinal layers remain unchanged, which means that the difference in mechanical properties between standard CLT slabs and CLT slabs with REX transverse layers is limited. CLT panels with transverse layers made of REX lamination can significantly limit the carbon footprint by reducing the need for virgin material for producing a panel. CLT with transverse layers of REX lamella have on several occasions been produced in a production line at one of Stora Ensos pulps and used successfully in projects. A stack of five CLT-panels with REX lamellas are shown in Figure 2 (b).

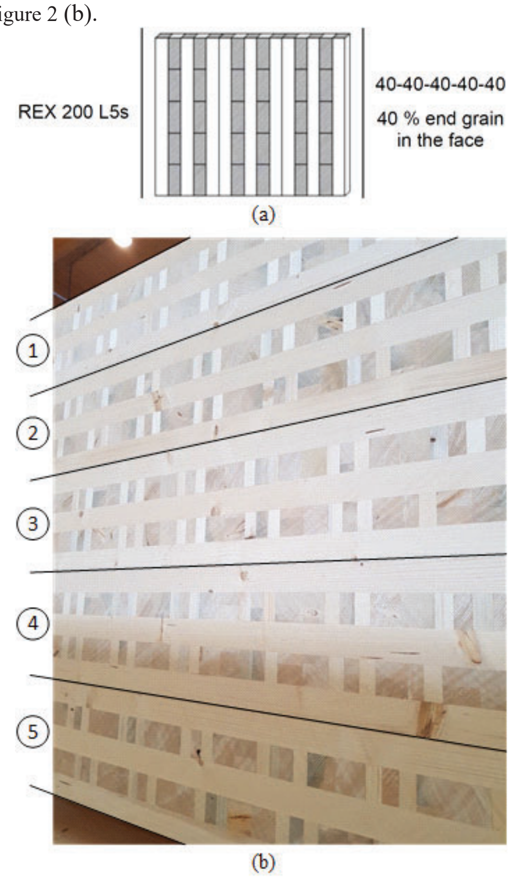

Figure 2: *a) Example of a REX lamination layer from a 5-ply CLT panel, from ETA-14/0349 [1] and b) photo of a stack of five CLT-panels with REX lamellas.*

3. CLT-BOARDS AS SUPERIOR RAILS IN TIMBER FRAME STRUCTURES

In multi-storey timber frame buildings the horizontal rails are often a weak point and the accumulated vertical deformations occasionally become problematic. Extra wall studs are at times needed to distribute the load onto a larger area on the rail and thus decrease the stress. By using CLT-boards as rails this problem is minimized thanks to the superior transverse properties. Since every other layer in a CLT-board has the fiber direction in the direction perpendicular to the length direction of the rail and in parallel to the stud, it can carry a much higher perpendicular load compared to structural timber.

Tests of the transverse properties were carried out on 50+50 CLT-boards cut from 5-ply (5·20 mm) CLT wall panels from the Stora Enso mill in Gruvön, Sweden, and on 15 specimens with similar dimensions using structural timber of quality C24. The boards were planed to the standard size 45·95 mm^2 and blocks were cut for the test following EN 408 [2]. In Figure 3 (a) and (b) the cross section of one of the tested specimens is shown together with the setup used for loading. The setup was designed

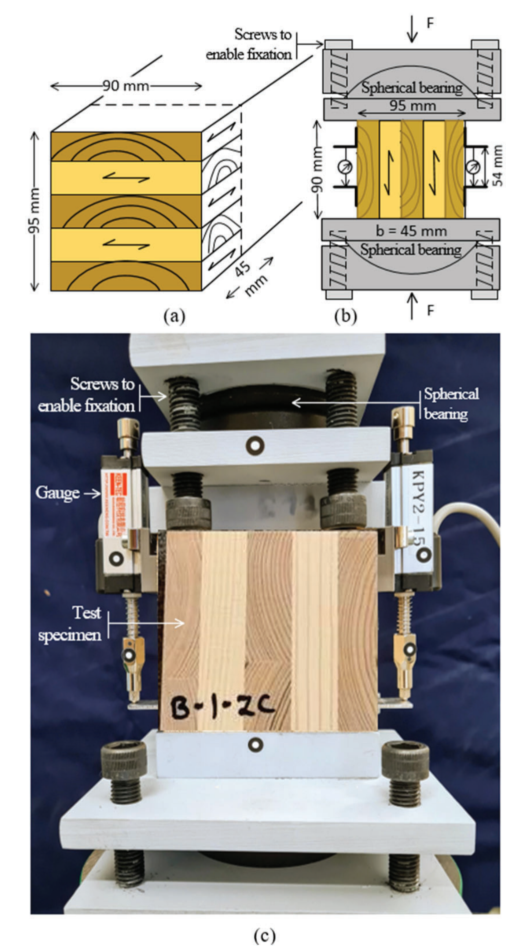

Figure 3: *Test specimen and setup used for testing the stiffness and strength.*

so that a spherical bearing was placed between two steel plates on top of the specimen and below the specimen respectively. Once a pre-load, being 0.2 kN, was applied any further rotation was prevented by means of four screws between the two steel plates fixing the configuration in desired position. The load was thereafter applied under displacement control at a constant displacement of 3 mm/min until a total of at least 2.5 mm. The vertical relative displacement was measured by means of two gauges placed centrically with respect to the height, one on each side of the specimen, measuring the variation in length between the two attachment points on each side being originally 54 mm apart. The data collected was used for calculating the stiffness and the strength of the material tested.

According to the EN 408 [2] the stiffness of the material is to be calculated as

$$E_{c.90} = \frac{(F_{40} - F_{10})h_0}{(w_{40} - w_{10})bl} \tag{1}$$

where F_{10} and F_{40} are the loads at 10 and 40 % of the compressive strength $F_{c.90.max}$ respectively, h_0 is thevertical distance between the measuring points w_{10} and w_{40} the deformation corresponding to the 10 and 40 % load levels and finally b and l the cross-section dimensions of the specimen. The strength of the test specimens was calculated as

$$f_{c.90} = \frac{F_{c.90.max}}{bl} \tag{2}$$

with obvious similar notations. A selection of results from the performed test series are presented in Table 1. Within parenthesis are the variation expressed as a percentage of the average. Since the moisture content was different in the specimens the result presented is compensated in line with the standard [2] to match M.C. = 12 %.

Table 1: *Table showing average values for performed material tests.*

	Structural timber, C24	Two layers par.	Three layers par.
n	15	50	50
Dens. [kg/m³,%]	465 (6.8)	481 (2.9)	472 (4.0)
M.C. [%,%]	10.73 (2.9)	9.41 (2.4)	9.03 (3.3)
$E_{c.90}$ [MPa,%]	357 (14.7)	5552 (33.8)	7094 (55.7)
$f_{c.90}$ [MPa,%]	3.48 (9.2)	20.16 (8.2)	29.24 (12.1)
$f_{c.90,.05}$ [MPa,%]	- (-)	17.16 (-)	24.37 (-)

Table 2: *Stiffness values used for the simulation of orthotropic material.*

E_l = 12 GPa	E_r = 1.1 GPa	E_t = 800 MPa
G_{lr} = 750 MPa	G_{lt} = 750 MPa	G_{rt} = 50 MPa
ν_{lr} = 0.05	ν_{lr} = 0.05	ν_{lr} = 0.4

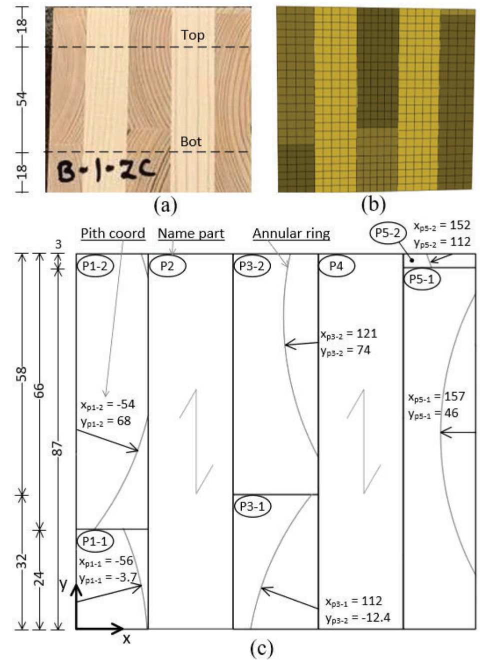

Figure 4: *Pith location for the boards in a selected specimen analysed by use of FEM.*

This way of evaluating the stiffness and the strength for material loaded perpendicular to the grain has been used successfully under long time, but as it turns out it is quite challenging to use for analysis of the CLT-boards due to their variable stiffness in various parts of the material. This will be addressed and exemplified by use of three selected specimens, one of each type tested, in the following. Such analysis is made possible due to the use of a Digital Image Correlation (DIC) system utilized for some of the specimens tested as a complement to the gauges previously described.

One of the tested specimens, of the sort with two layers with fibres in parallel to the loading direction, were analysed by means of the finite element method. The elastic analysis was performed so that the orthotropic material used followed the cylindrical coordinate system defined by the pith of each of the annular rings (assumed circular) in the visible cross sections of the boards, see Figure 4 (a) and (c). The mesh, with second order elements with reduced integration, used to analyse the

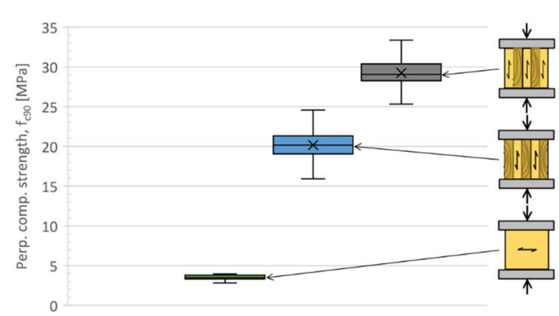

Figure 5: *Perpendicular compression strength f_{c90} of 5-ply CLT-boards compared with standard C24-timber.*

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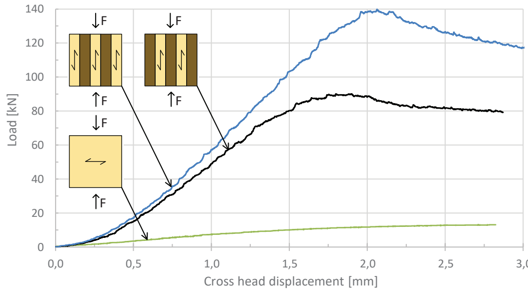

Figure 6: *Load displacement curves for three typical test specimens, one of each type tested, i.e. three parallel layers, two parallel layers and structural timber.*

loading of the specimen is illustrated in Figure 4 (b), each of the parts defined coded with a specific nuance of the brownish colour.

The tests of the perpendicular compression strength showed that a CLT-board had a capacity of 5-8 times the capacity of a standard C24 timber, depending on the proportion of transverse cross layers, see Figure 5. For the case with three layers in parallel with the load direction, corresponding to 57.4 % of the cross-section area, the average of the 50 specimens was calculated to $f_{c90.3par} = 29$ MPa, see Figure 5. For the other case with two layers in parallel with the stud length direction, corresponding to 42.6 % of the cross-section area, the average strength was calculated to $f_{c90.2par} = 20$ MPa. Finally, for the tested specimens of structural timber, quality C24, the strength was calculated to $f_{c90.C24} = 3.5$ MPa on average. The results indicate the considerable potential for making use of the products in loading situations where timber is loaded perpendicular to the length direction of the board, e.g. in rails in prefabricated planar of module building elements.

Yet another property worth pointing out is the post peak behaviour. The load displacement curves for one representative test specimen of each type is shown in Figure 6. For the two CLT-boards the post peak load is falling, but there is no sudden considerable loss in load bearing capacity representing a fatal collapse. Rather, a plateau is reached and the material exhibit plastic behaviour at a load corresponding to the peak load reduced by 10-15 %.

Finally, the curves in the figure indicates a considerably higher stiffness in the CLT-boards compared to the structural timber. At this stage however it should be noted that the horizontal scale in the graph represents the cross head movement rather than the individual or average values of the two gauges installed on each side of the specimen. This means that any boundary effect along the top or bottom loading surfaces

Table 3: *Stiffness's and strength values for three specimens, one of each type tested.*

	Structural timber, C24	Two layers par.	Three layers par.
$E_{c.90}$	160 MPa	1.49 GPa	1.86 GPa
$f_{c.90}$	3.11 MPa	21.1 MPa	32.7 MPa

respectively will be included in the curves. Accepting this the stiffnesses equated by use of (1) can be calculated to values presented in Table 3.

The explanation to why the cross head displacement is used rather than values from the gauges is revealed by the results from the DIC. In Figure 7 (a) the test specimen with two layers having their longitudinal direction in parallel to the loading direction (and with the partitioning and annular rings according to Figure 4) is shown at peak load ($F_{c.90.max} = 89.6$ kN) and with an overlay of strains in vertical direction at that given load level. It is evident from the strain concentrations at some specific localizations that local properties such as variations in stiffness, inclined fibres or a glue line between two layers of boards, will affect the properties of the specimen. To further investigate this the vertical displacement is plotted at the peak load along two lines, referred to as "top" and "bot" in Figure 7 (a). The result is presented in subfigure (c) and the relative distances between the two ("top" and "bot") lines is in turn shown in subfigure (d).

Not only are these results shown for the specimen described, but also for two other specimens, one from structural timber and one with three layers oriented with their fibres parallel to the loading directions. These results are shown in the two same graphs. Finally, subfigure (e) and (f) show the same thing but at 30 % load level compared to the peak load. The relative difference in vertical displacement between the "top" and the "bot" lines clearly indicates the challenges associated with the measuring technic often utilized to perform measurements used to calculate the stiffness $E_{c.90}$. The subfigures (d) and (f) show that in particular for the CLT boards, the relative length between the two lines is varying considerably over the section. This applies for peak load (c) and (d) as well as within the typical range used to calculate the stiffness, e.g. 30 % of the peak load, see subfigures (e) and (f). Based on this it is recommended simply to use the cross head displacement for the calculation of the stiffness values in case of CLT-boards. This will give conservative stiffness values in general.

At last Figure 7(b) shows results from the FE-simulation performed for the selected and previously discussed specimen with two layers with their fibres in parallel to the loading direction. Displacements are magnified by a factor 5 and maximum stresses $\sigma_{yy} \approx 58$ MPa are obtained in the two layers oriented with their fibres in the y direction.

4. CLT-BOARDS AS INTEGRATED GLULAM LAMINATIONS

When designing glulam beams with long spans there are occasionally critical design issues related to stress levels perpendicular to the fibers involved. According to the Eurocode [3] the design compressive stress in the contact area perpendicular to the grain $\sigma_{c,90,d}$ for a single supported or continuous beam should be less than the design compressive strength perpendicular to the grain, $f_{c,90,d}$, multiplied by a correction factor $k_{c,90}$ so that

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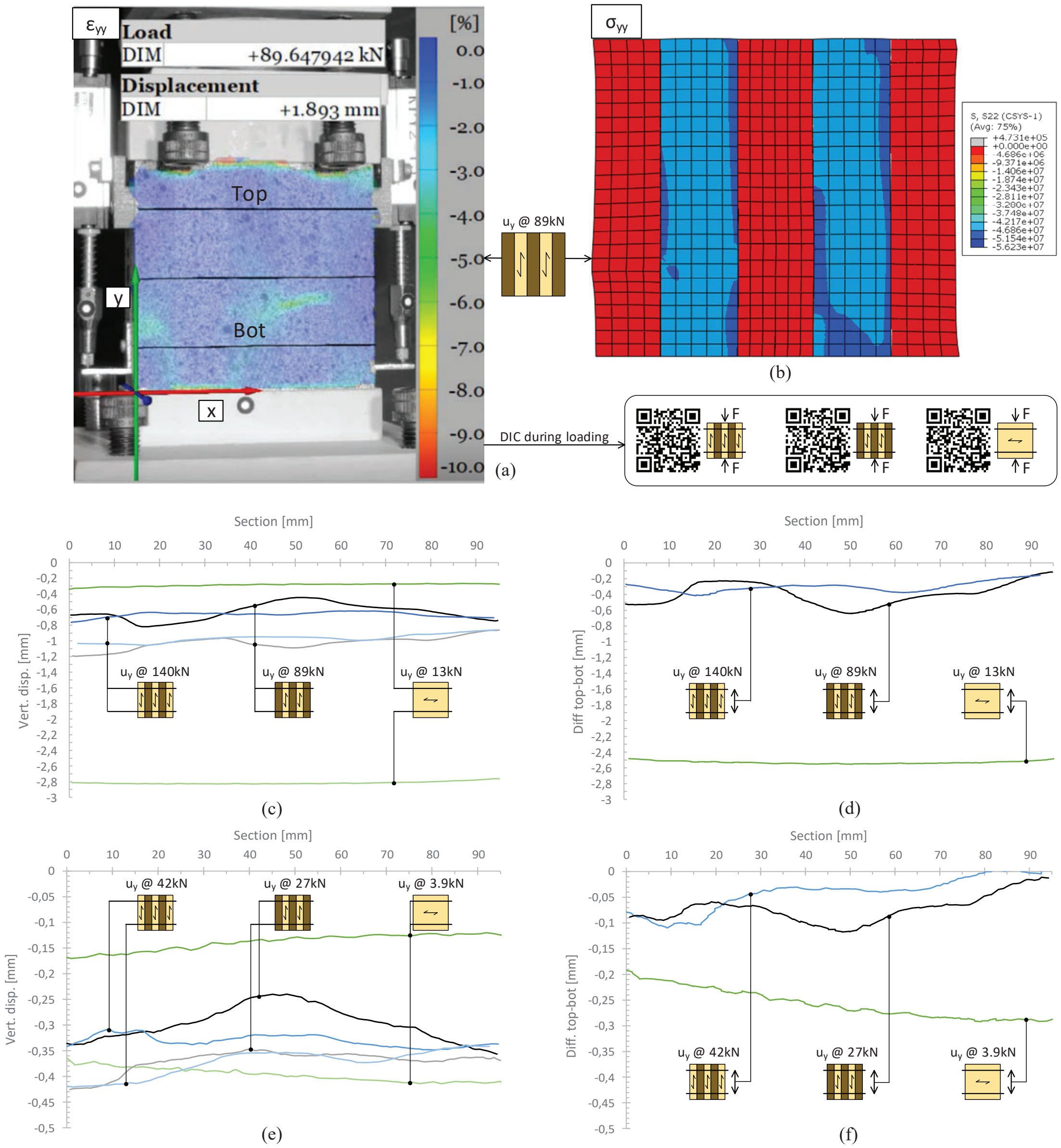

Figure 7: *Results from a) DIC during loading of specimen with two layers with longitudinal direction in parallel to the loading direction and b) results from stress component σ_{yy} from FEM-simulations of the same specimen and vertical displacement of reference lines at c) and d) peak load and e) and f) at 30 % of peak load.*

$$\frac{F_{c,90,d}}{A} = \sigma_{c,90,d} \leq k_{c,90} \cdot f_{c,90,d} \tag{3}$$

For a beam with a depth $h > 2{,}5\ b$ resting on a support closer than $h/3$ to the beam end or on internal supports respectively the factor k_{90} is obtained as

$$k_{c,90} = (2.38 - \frac{l}{250})(1 + \frac{h}{12l}) \tag{4}$$

$$k_{c,90} = (2.38 - \frac{l}{250})(1 + \frac{h}{6l}) \tag{5}$$

where l is the contact length between column and beam. For a reference continuous beam 86 · 315 mm in cross-section being supported internally by a column with full beam width and l = 90 mm the design load can be calculated to $F_{c,90,d}$ = 47 kN (γ_M = 1.25, k_{mod} = 0.8).
The phenomenon with high stresses perpendicular to the fibers in the vicinity of supports has been the subject for several research studies [4, 5] and various suggestions have been made how to address the issue. These suggestions include to increase the contact length l (and thus the contact area) e.g. by placing a stiff and strong steel plate between the beam and the column, see Figure 8(b), to fasten long self-tapping screws into the beam so

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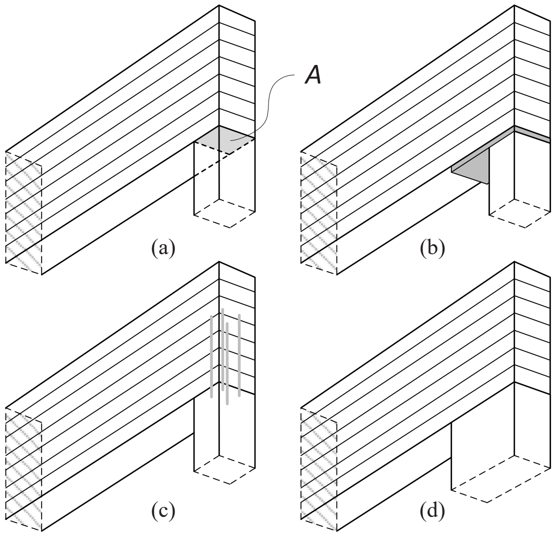

Figure 8: *a) Area loaded perpendicular to grain b) example of steel plate in the contact area between column and beam c) screws for distribution of the load and d) increased column area.*

that the forces are distributed into the beam [6], Figure 8(c), or to simply by increased dimensions of the column, see Figure 8(d).

In the current study another method is suggested to increase the stiffness and strength for a glulam beam loaded perpendicular to the grain in the support area. 1, 2 or 3 of the lamellas in the glulam beam located closest to the column are substituted by CLT-boards from a five layer CLT-panel. These are of type 1, see Figure 1, so that two of their layers are oriented with their longitudinal fiber direction in parallel to the length direction of the column. The CLT-boards were glued to the GLT beam by use of a polyurethane glue and cured for 4 hours under a constant pressure corresponding to 0.5 MPa. An example of an end support and an internal support for a glulam beam when 1 lamella is exchanged locally to a CLT-board is illustrated in Figure 9. Note that the CLT-board is finger jointed to the conventional lamella and that it might also include a finger joint itself.

Modified glulam beams with the dimensions according to Figure 1d were loaded under displacement control to a 15 mm piston displacement. In addition to the beams enhanced by 1, 2 or 3 CLT-lamellas, a reference glulam beam (GLT) without CLT-lamellas was included in the test series as well as a GLT-beam with a 12 mm thick steel plate being 86 · 200 mm in dimensions placed centrally in between the column and the GLT-beam. For each of the five types of setups, A-E, five specimens were tested. An illustration of the setup for the experimental test is shown in Figure 10, see also [7].

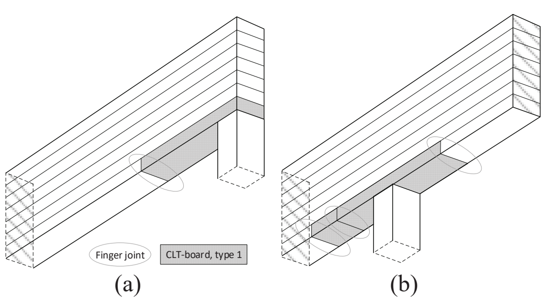

Figure 9: *Illustration of the concept for obtaining increased stiffness and load bearing capacity in a GLT beam for a) end support and b) internal support.*

The average load-displacement curves for the five specimens per setup, shown in Figure 11, indicates a surprisingly high increase in stiffness and strength when 1, 2 or 3 CLT laminations are built into the glulam compared to the reference conventional GLT-beam. It can be noted that the maximum applied load was slightly higher for the case with a distributing steel plate compared to that with a setup including one lamella made out of a CLT-board. However that load-level was obtain at substantial displacements, e.g. larger than 8 mm.

In Table 4 the stiffness, k, and the maximum applied force, F_{max}, is showed as an average of the five tested specimens in each setup. The stiffness is obtained as

$$k = \frac{0.4F_{max} - 0.2F_{max}}{u_{0.4Fmax} - u_{0.2Fmax}} \quad (6)$$

were F_{max} is the maximum applied load and u_x is the displacement at 40 and 20 % of that load respectively. In addition to the stiffness and maximum load the table shows each of the two normalized against the reference GLT beam E, i.e. the quota k_x/k_E and $F_{max.X}/F_{max.E}$. It is striking that by use of three CLT-lamellas the stiffness can be increased by 98 % and the maximum applied load may be 132 % higher compared to the reference beam E.

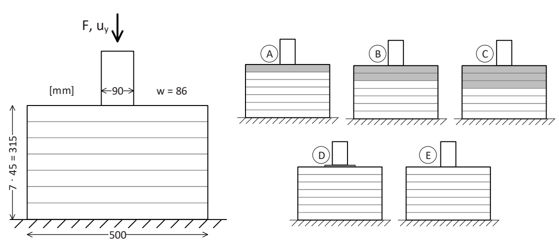

Figure 10: *Geometry and load cases for each setup and illustration of the five different setups, A-C with included CLT-boards, D with a steel plate and E with a pure GLT-beam as a reference.*

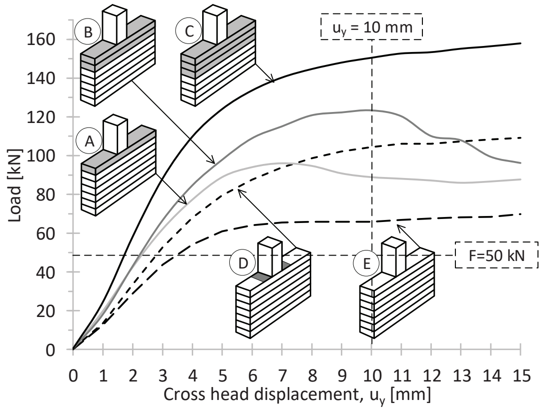

Figure 11: *Average load-displacement curves from experimental tests of 1, 2 and 3 CLT laminations in the beam and GLT beam with and without steel plate.*

Finally the piston displacement u_y at the design load $F_{c.90.d}$= 47 kN is given in the table. The displacement of the reference beam E is almost double that of the beam with three CLT-boards at that load.

For at least one of the specimens in each setup digital image correlation (DIC) was used for taking stereoscopic pictures during the loading event. In Figure 12 strains in vertical direction (ε_y) are shown at a load F = 50 kN and at a piston displacement u_y = 10 mm respectively. The black horizontal lines in the photos of the GLT indicates the centre of each lamella. Note that the scale for the strains are the same in all subfigures. Red colour indicates larger strains and blue is representing small strains and the total span for the scale is $0 \leq \varepsilon_y \leq 0.01$. For each setup a 20 sec film sequence showing the whole load event can be found if the qr-code at the right is followed and there a scale with the strains is included. One result worth noting is the relatively small strains in the CLT-boards. From the photos in the figure this is particularly clear for setup B and C. This is explained by the high stiffness in the CLT-boards achieved by the lamellas oriented in parallel to the load direction.

Table 4: *Stiffness and maximum applied force for the tested setups.*

Setup	k [kN/mm]	F_{max} [kN]	k/k_E	$F_{max}/F_{max.E}$	u_y@ $F_{c.90.d}$ [mm]
A	23.1	96.8	1.35	1.39	2.22
B	24.8	122.6	1.44	1.77	2.20
C	34.0	161.0	1.98	2.32	1.67
D	20.5	109.2	1.19	1.57	2.69
E	17.2	69.4	1.00	1.00	3.27

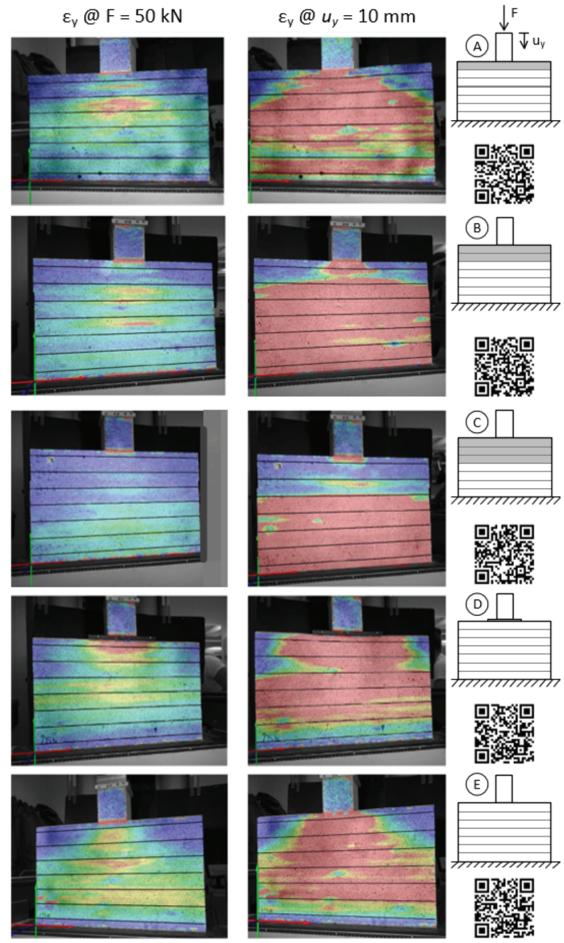

Figure 12: *Photos from DIC with strains in vertical direction (ε_y) for the load F = 50 kN and at a piston displacement u_y = 10 mm.*

5. CONCLUSIONS

In this paper, three concepts of re-use of cut-offs from CLT are presented.

a) The re-use of cut-offs as REX laminations in CLT production is a smart concept that minimize waste in an economical way.
b) By using finger-jointed CLT-boards as horizontal rails in timber frame buildings, the problems with high local compression perpendicular to the grains and large vertical deformations in multi-storey houses are minimized.
c) The capacity of glulam beams to carry concentrated loads is greatly enhanced by locally integrating CLT-boards as laminations.

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