LESS IS MORE – OPTIMISED RIBBED CLT PLATES – THE FUTURE

Authors:
Iztok Sustersic[1,2]
Dr Bruno Dujic[2]
Dr Simon Aicher[3]

[1] University of Ljubljana, Slovenia
[2] CBD d.o.o., Slovenia
[3] MPA Otto Graff Stuttgart, Germany

Email: iztok.sustersic@cbd.si

ABSTRACT

This paper presents a new type of cross laminated timber (CLT) plates called "Xlam ribbed plates" (XR-lam), with timber ribs glued within the CLT plate's structure. The main objective of the newly proposed plates is to optimise the structural performance of regular CLT in terms of material use by incorporating the ribs into the main panel's structure in a single production process and without increasing the production costs. The new plates were numerically modelled and experimentally tested both as floor and wall elements. Apart from a much better material utilisation, they demonstrate high load bearing properties and resilient behaviour.

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Less is more – optimized ribbed CLTs – the future

1. Introduction

Cross laminated timber (Xlam or CLT) has started its mass production about 15 years ago. Over time it has become one of the most used products in the timber construction industry with its worldwide use growing exponentially [1]. As the quantity of yearly cut timber especially in Europe is slowly reaching its maximum, its price is consequently rising, making conventional Xlam less competitive on the market on one hand and more straining on the forest on the other hand. Xlam technology has still lots of potential for improvement in several aspects that would allow for more effective and economic use under different boundary conditions; namely loads, spans, fire resistance, seismic performance, etc.

This paper presents a new type of cross-laminated timber plates that address a part of these issues. They are called “Xlam ribbed plate” (XR-lam), with timber ribs glued within the Xlam plate’s structure (Figure 1). The main objective of the newly proposed plates is to optimise the structural performance of regular CLT in terms of material use by incorporating the ribs into the main panel’s structure as well as simplify their production. Such elements could present a more competitive and forest friendly alternative to conventional CLT.

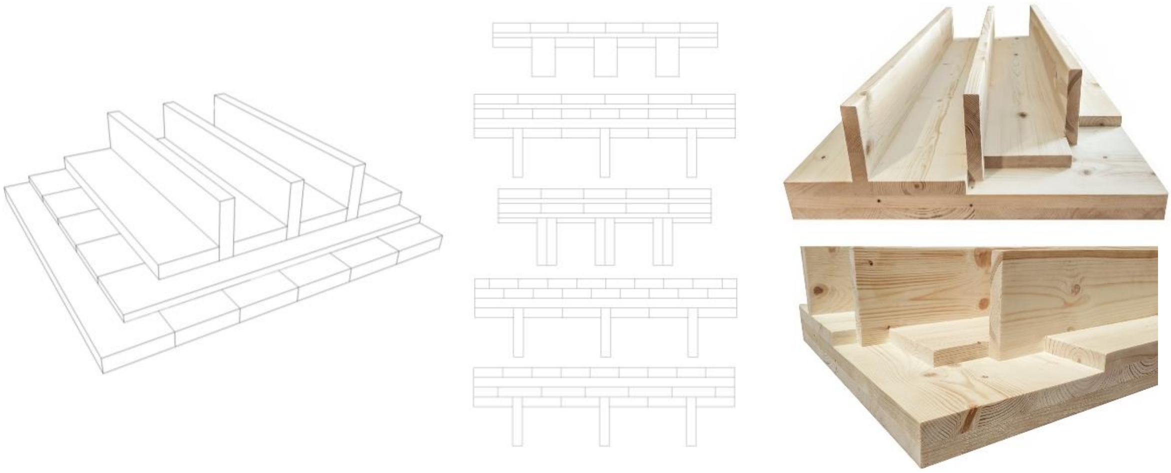

Figure 1: A basic Xlam ribbed plate structure and various rib combinations

There is already a demand for ribbed-type plates on the construction market. Currently the main use of such plates is for floor and roof panels with larger spans. Conventional CLT is cost-effective up to spans of about 6 m (Figure 2). Above that it is more feasible to use a combination of primary beams and thinner CLT on top, or to produce custom made combinations of beams and plates glued (or just screwed) together. The aim of the proposed XR-lam plates is also to close the gap between and make the 6-8 m spans easier to bridge without unnecessary cost and material consumption.

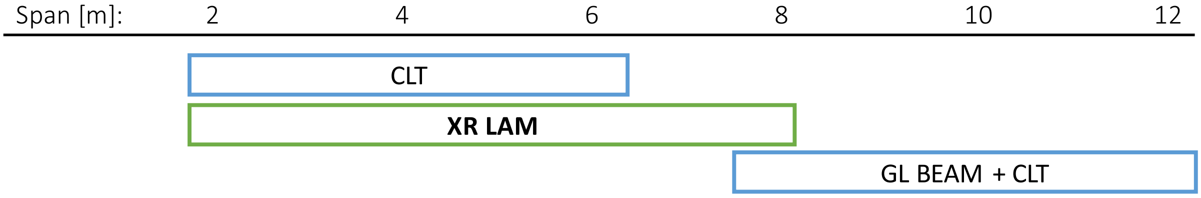

Figure 2: The target span area for the new Xlam-ribbed (XR-LAM) plates

The second main field of the XR-lam plate use is for walls with ribs on the outer side of cross-laminated timber panels (Figure 3) that serve as a sub-construction for insulation and a façade. Hence the construction process can be sped up as the final building layers (insulation, façade etc.) can be installed easier and material for an additional sub-façade structure is not needed any more. In addition, ribbed wall elements also allow for higher buckling resistance. Consequently, such elements ensure a more effective construction with lower timber consumption and altogether lower production and assembly costs.

Figure 3: Combining a light timber frame with a CLT panel results in an effective XR-lam wall element

Combining CLT and glue-laminated or massive timber beams into a ribbed-type structure in current engineering practice is performed as a two-step process. This means additional plate and rib manipulation and potential use of additional mechanical fasteners. By incorporating the ribs into the main cross-lam structure, forming a new type of the outer side lamella pattern and unifying the ribbed-plate production process, time and costs are saved. Also, very narrow ribs can be used (Figure 4) due to the secure positioning in the stable cover layer structure.

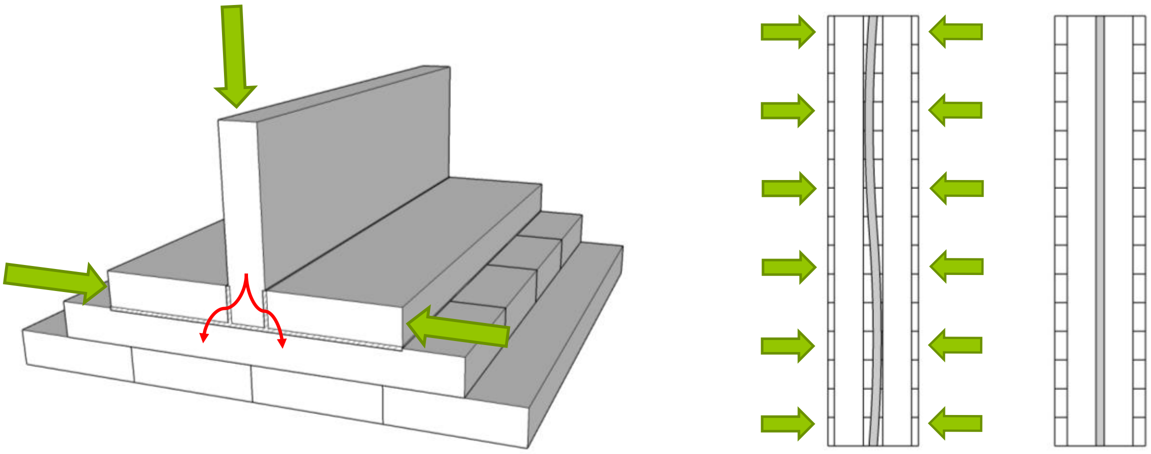

Figure 4: Advantages of narrow boards and side pressing

Hereinafter the paper describes the development procedure of the ribbed plates that was part of the HCLTP (Hybrid Cross Laminated Timber Plates) European research project [2]. The project dealt with different kinds of improved CLT plates, however its main focus was on the ribbed plates. The main aspects of the ribbed plate development are presented; the numerical modelling, optimisation of the cross-section geometries and material choice, keeping in mind the boundary conditions necessary to keep the new production line feasible. The production of test specimens on a prototype multiaxial press is also shown as are the results of some of the experimental tests (4-point bending tests of floor elements and a wall compression-buckling test).

2. Numerical modelling

Development of finite element models (FEM) of the proposed ribbed plates and walls served to find optimal values of the following variables: plate geometry (layer thickness, number of layers), plate span, rib geometry and spacing, effect of side-gluing of ribs, material grades, etc. under different boundary conditions (load, edge supports, etc.) in terms of ultimate limit state (ULS) and serviceability limit state (SLS) requirements. The optimisation process had a goal of achieving combinations with the least material used while still being within pre-defined stiffness and load bearing capacity.

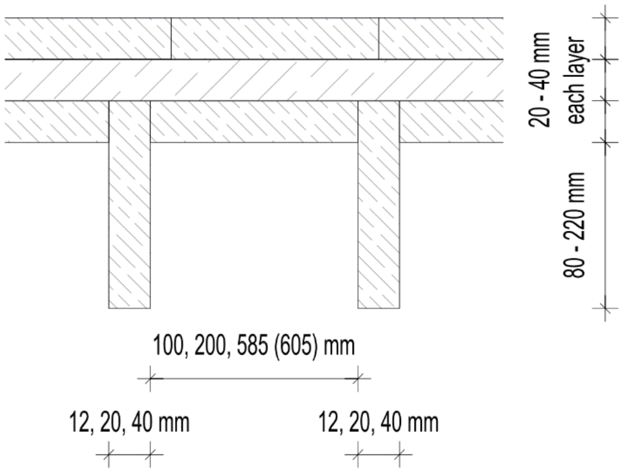

Figure 4: The ribbed-Xlam plate geometries selected for further production development and testing

Apart from the geometrical and material properties a very important factor is also the material price. In that term the raw timber lamellas present the best option for an efficient, yet affordable composition. In general, high and narrow lamellas turned out to be very efficient in terms of material use.

The spacing between the ribs was finally determined based on the possibilities the new production press could have without being too complex and hence too expensive to produce as well as maintain. Therefor (Figure 4) a 100 mm basic modular spacing was chosen with an additional 585 (605) mm distance for cladding sheet optimisation (i.e. hard insulation plates on the façade). The desired rib thickness is 16-40 mm. The rib height is bound by the timber lamella dimensions which are in most cases up to 240 mm. Hence the rib portion protruding outside of the plate can be up to 220 mm. Individual layers of the massive part of the ribbed plate are 20-40 mm thick which is already standard with some of the regular CLT producers. Only three layer plates have been chosen for further production development as adding more layers to the plate does not have a high enough beneficial effect. The three-layer setup still offers all the benefits of regular CLT (high in-plane stiffness, robustness etc.), yet takes full advantage of the ribs. It should be noted, however, that as far as the fire performance is considered the narrow ribs must be covered with a protective cladding for fire demands above 30 minutes. For R30 values [3] the compression timber plate of 120 mm thickness suffices, regardless of the rib dimensions. Though, if the plate is turned upside down and the ribs are on the upper side, fire resistance over 60 minutes can easily be achieved for any geometry setup.

In the following figure (Figure 5) a comparison of timber consumption between regular and the new ribbed CLT is performed on a single span roof element (self-weight of the plates + additional dead load of 0.6 kN/m^2 and snow load of 1.3 kN/m^2). Only stresses and displacements were considered. A comparison is also shown for a timber floor element (self-weight of the plates + additional dead load of 2.0 kN/m^2 and live load of 2.0 kN/m^2), where apart from stresses and displacements also vibrations are checked (and are the governing criteria in all cases). Less strict criteria for vibration (class II according to [4]) valid for one-family housing was considered in combination with 4% damping (assumption of a floating concrete screed) and a 5 meter effective (room) width. All the lamellas are assumed to be of C24 strength class [5].

The ribbed Xlam (XR-LAM) elements labels represent the following: "plate thickness – rib width / rib height @ rib spacing". Therefor XR-LAM 60-40/170@240 means a ribbed plate with a 60 mm (20-20-20) thick 3-layer plate and 40/170 mm ribs (height protruding from the plate) spaced at 240 mm centre-to-centre. It should be noted, however, that the rib heights were calculated to enable a direct comparison with conventional CLT plates. In practice the rib height would be confined to a 20-mm step. The conventional CLT plates used for comparison have the following layer setups in mm: 100 (30-40-30), 120 (40-40-40), 140 (40-20-20-20-40), 160 (40-20-40-20-40), 180 (40-30-40-30-40), 200 (40-40-40-40-40) and 240 (30-40-30-40-30-40-30) with C24 lamellas.

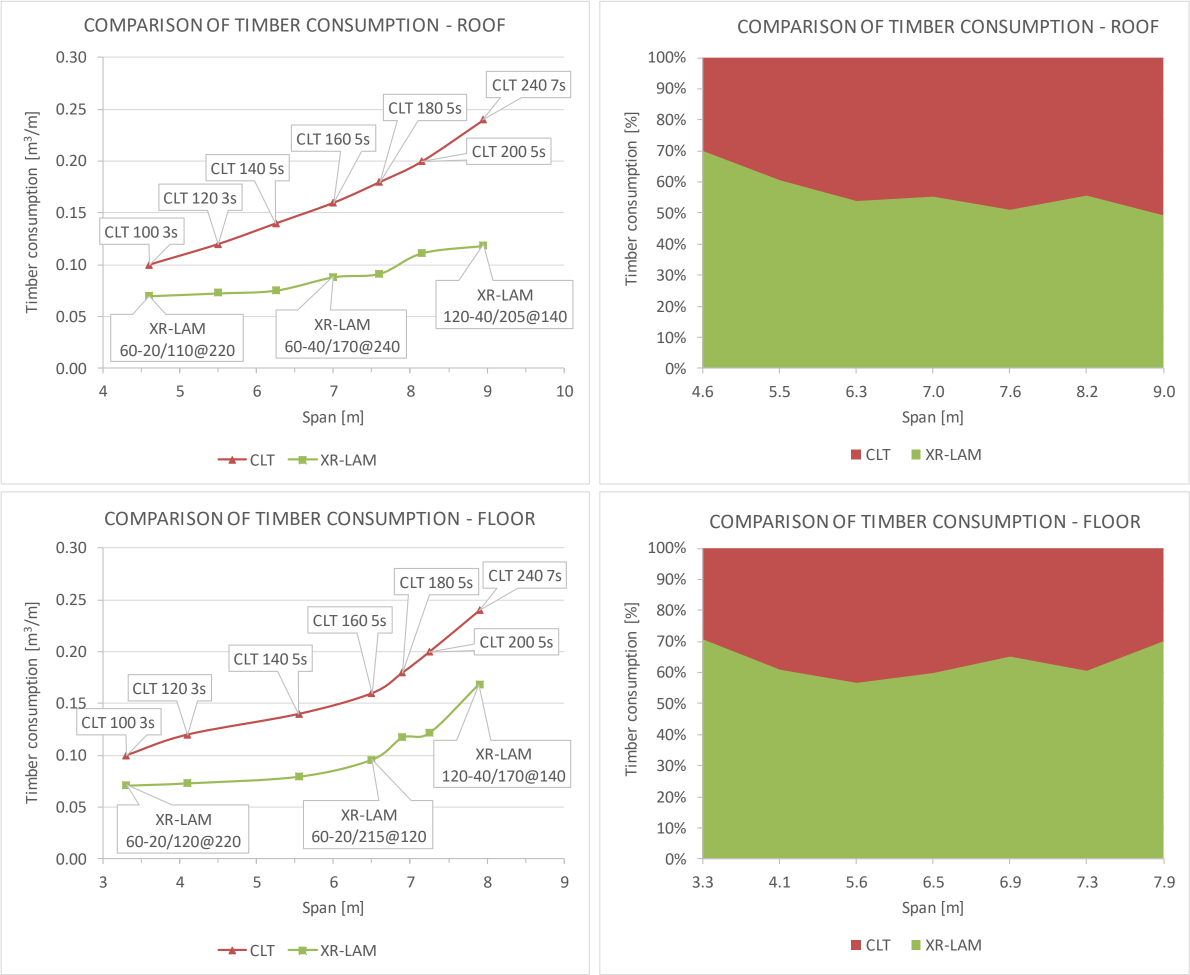

Figure 5: Comparison of timber consumption of Xlam ribbed plates compared to regular cross laminated timber plates

The study shows that Xlam ribbed plates could save 25-50 % of timber to achieve the same effect. The difference in material consumption is smaller for larger spans. On the other hand, the height of the ribbed plate cross sections is 20-90% higher. Nevertheless, the space is not lost as the installations of various sizes can be run through the void spaces between ribs. The ribs also enable the installation of a secondary sound insulation and a lowered ceiling for an improved acoustic performance.

3. Element production

A prototype press was assembled at the company Ledinek d.o.o. in Slovenia. A segment of their standard X-press system was modified to enable the production of new ribbed plate specimens up to 1.5 x 4.0 m.

The press is pneumatic, namely rubber airbags are mechanically lowered into positions over the plate specimens and inflated with air. Each tank can be inflated up to 15 bar. The used pressure was lower; it was calculated individually for each specimen type to achieve the 0.8 N/mm^2 in the polyurethane glue lines. For gluing Purbond HB 110 adhesive was used with the KLP's Profipur 3000 system installed to apply it. The side pressing of specimens was also pneumatic over airbags as demonstrated in the following figure (Figure 6). The vertical pressing was established with the help of dummy elements to fill the voids between the ribs. The dummies were planed to exact height to establish a flat pressing surface on top of the specimen.

Figure 6: Large specimen production; vertical pressing over dummy elements and side pressing

Over 40 floor and wall elements (Figure 7) were produced. Some of them being comparison specimens made from regular Xlam plates with ribs glued directly onto them with a special stabilisation system. Most of the elements are intended for four-point bending testing. Apart from floor elements, also wall segments were made with a wider rib spacing. These wall elements were tested for buckling strength and stability.

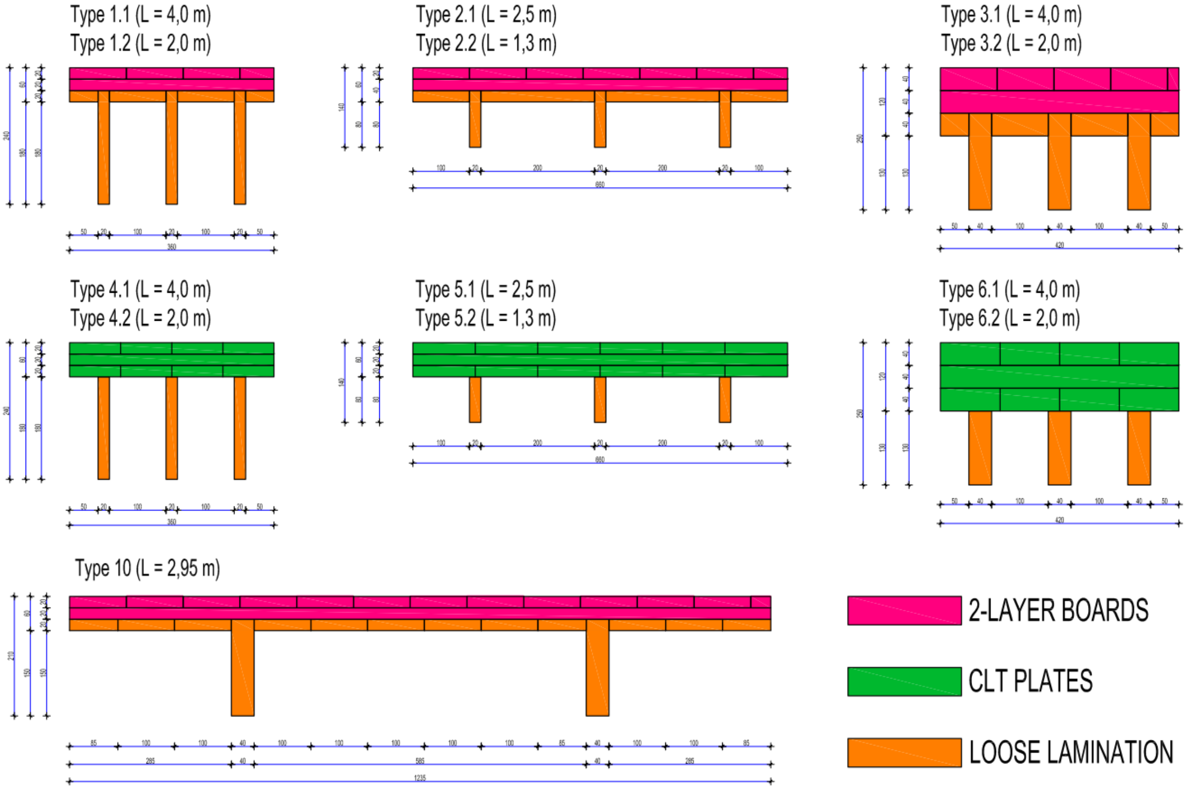

Figure 7: The variation of test ribbed plate geometries produced for experimental testing

Before the elements were produced all the lamellas were graded and the dynamic modulus of elasticity was measured. The lamellas intended for ribs were spread equally among specimens. Namely, within each specimen ribs have different stiffness properties – one of highest stiffness, one of medium and one of the lowest stiffness.

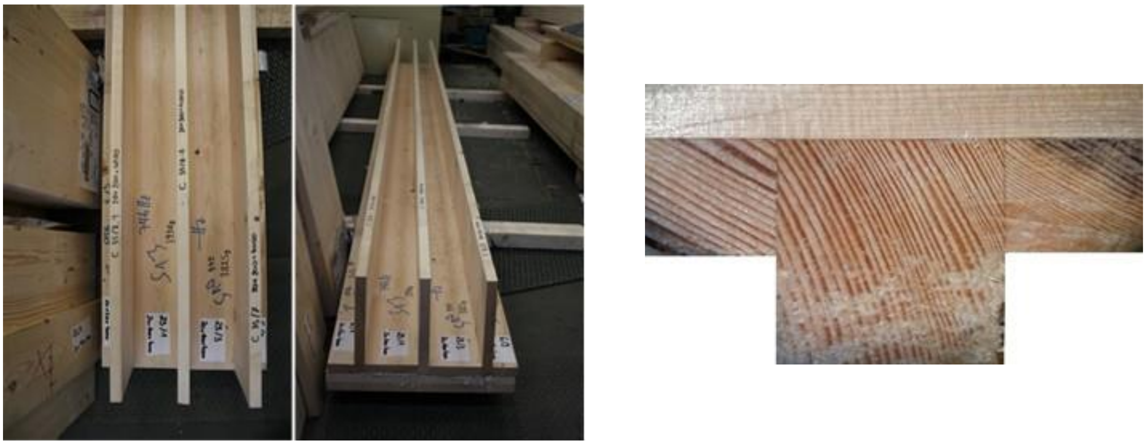

Figure 8: One of the final specimens and the glue lines around the rib

The glue-lines (Figure 8) established during production were kept below 0.3 mm according to the demands for polyurethane adhesives.

Overall what was learn during test specimen production is that gluing narrow ribs onto a conventional CLT plate can be problematic. Additional supports had to be made and connected into the CLT plate to prevent the rib from buckling under pressure on one hand and keeping it straight (lengthwise), especially for narrow elements.

4. Experimental testing

An experimental test program at MPA Otto Graf institute of prototype setups was focused on in-plane bending tests of ribbed timber slabs and vertical buckling tests of XR-lam wall elements. Out-of-plane 4-point bending tests are being performed according to standard EN 408:2010 [6]. Some of the plates were tested for bending with the ribs facing down, some with ribs facing up. Results of the former are presented herein. Effective widths of the ribbed cross laminated plates' massive slabs were analysed by shear deformation lag in the slab plane. Two lengths of each geometry setup were tested tin order to provoke either bending or shear failure in the elements. Vibration modes were also measured.

The testing has shown that the ribbed plates exhibit an almost ductile behaviour with damage occurring progressively (Figure 9).

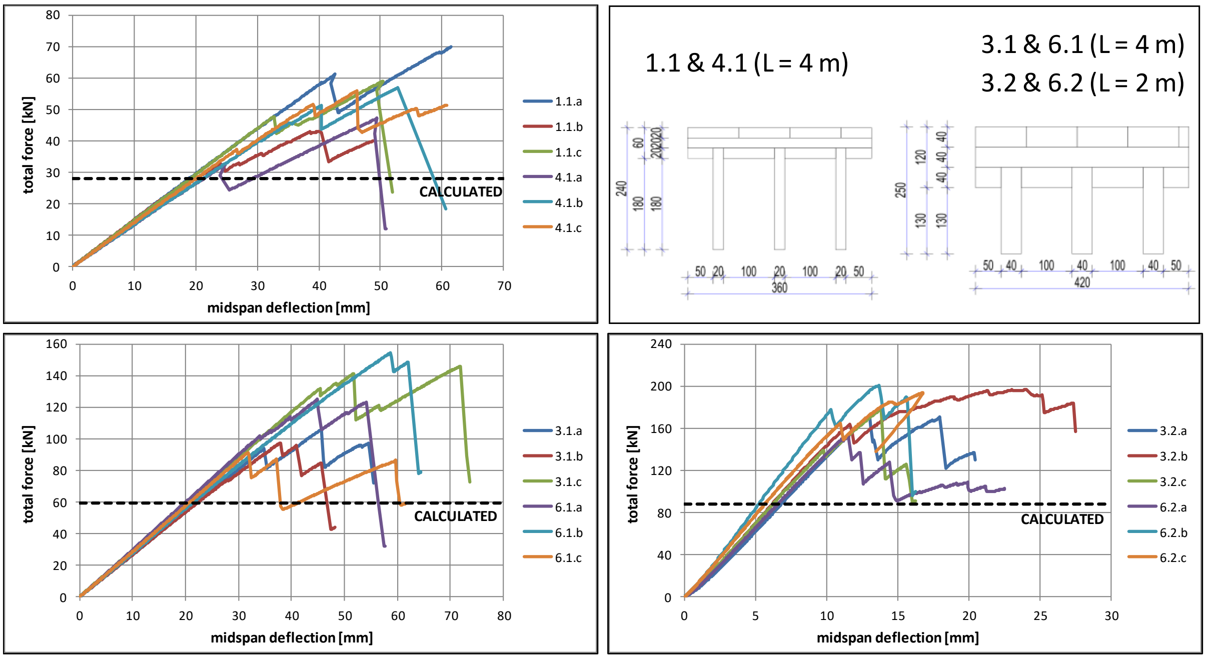

Figure 9: Midspan deflection – total vertical force curves for some of the tested floor elements

Figure 10: Damage in the XR-lam plates (either bending or shear) that occurs in several steps

Namely, after the first damage (bending or shear) develops in one of the ribs, the force is than redistributed to other ribs (Figure 10). After an initial drop, the force starts to climb again (Figure 9) until new damage occurs and so forth. Until the final failure of the last element (rib).

Since the ribs were close together, there was no distinctive shear lag response measured from the strain gages installed on the compression plate (Figure 11). Indeed, there was a difference in strains measured at different positions, however, the measurements were not correlated to whether they occurred over the rib or in-between the ribs. Instead they seem to be more bound to the elastic modulus (stiffness) of individual ribs.

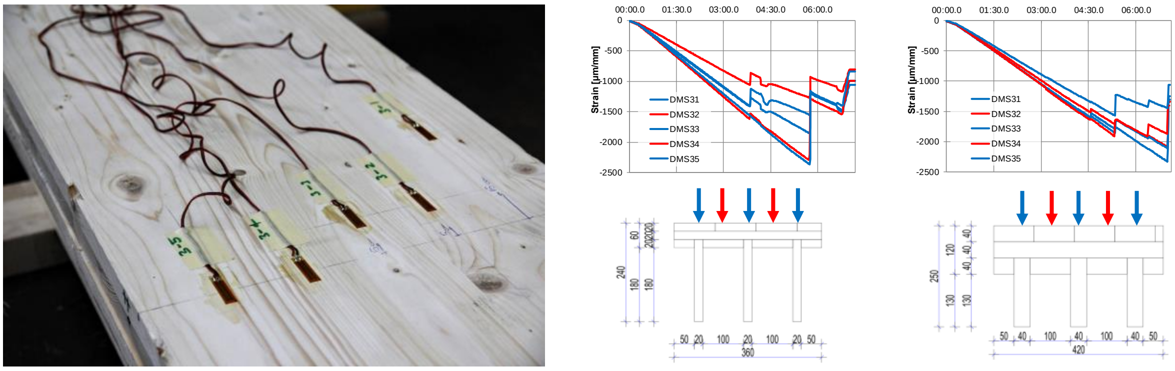

Figure 11: Strain gage distribution on top of the compression plate and measurements for two different cross sections

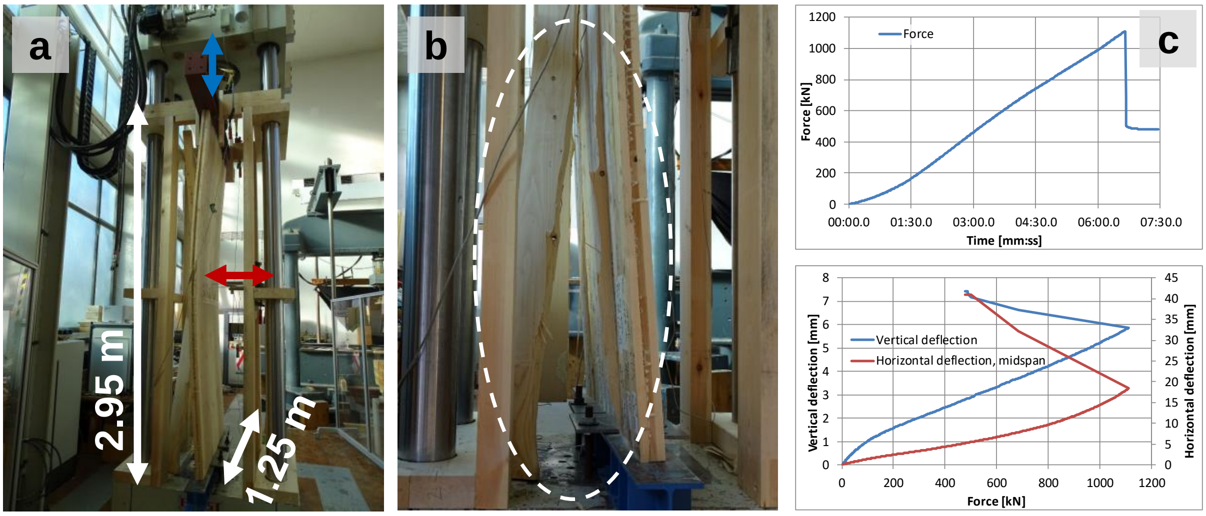

Figure 12: Wall specimen setup (a), local rib delamination (b), force and displacement measurements (c)

The wall specimens, 2.95 m high and 1.25 m wide were tested for buckling (Figure 12a). The specimens had a 6 cm thick compression plate and two ribs 4 cm wide and 15 cm high, spaced at 62.5 cm centre-to-centre. Only the compression plate was supported, the ribs were only increasing the bending strength and stiffness of the wall out-of-plane. The force introduction was linear without any sudden drops. The out-of-plane horizontal deflection was increasing constantly. At peak vertical load (1100 kN), it reached 18 mm (Figure 12c). At that point the ribs delaminated (Figure 12b) from the compression plate and the compression force dropped by about half. The (bent) compression plate could still support nearly 500 kN. Up to the point of rib delamination there was no sudden buckling of the wall as the compression behaviour of a non-symmetrical cross section is governed by axial bending. Since the vertical load was being introduced eccentrically, a bending moment was constantly present in the wall and the out-of-plane deflection was gradually increasing from the beginning.

5. Conclusions

The numerical analysis of ribbed cross laminated timber elements has shown that by using simple (and affordable) timber lamellas as ribs in the outer most layer of a cross laminated timber plate, up to 50% of timber can be saved compared to conventional CLT for roof elements and up to 40 % for floor elements, yet keeping the benefits of the massive system (in-plane stiffness, robustness etc.). By using a prototype press it was demonstrated that the elements can be successfully produced in a one-step procedure (assembling, gluing, pressing) lowering production costs compared to ribbed plates made so far. Experimental testing has shown favourable behaviour in out of plane bending of the new elements that exhibit progressive damage behaviour with redistribution of loads among ribs. The ribbed wall elements had demonstrated a high load bearing capacity (close to 0.9 MN/m). Overall the elements present an interesting alternative to conventional crosslam with their lower timber consumption and a lesser impact on the environment on one hand and competitive production costs on the other hand.

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