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XLAM RIBBED PLATES

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ABSTRACT: Cross laminated timber (CLT, X-lam) started its mass production in the beginning of the 21st century. Over time it has become one of the most used products in the timber construction industry with its worldwide use constantly growing. The quantity of yearly cut timber especially in Europe is slowly reaching its maximum and its price is rising. Hence conventional CLT is becoming more expensive and less competitive on the market on the one hand and more straining on the forest on the other hand. CLT technology has still lots of potential for improvement that would allow for more effective and economic use under different boundary conditions. This paper presents a new type of cross-laminated timber plates called the "Xlam ribbed plates" (XR-lam). The main objective of the newly proposed plates is to optimise the structural performance of regular CLT in terms of material use by incorporating ribs into the main panel structure as well as simplifying their production. Analyses show that such plates could use up to 50% less timber for the same performance as well as speed up the construction of the buildings' outer envelope. Hence, such elements could present a more competitive and forest friendly alternative to conventional CLT.

KEYWORDS: Cross-laminated timber, Hybrid plates, Experimental testing, Ribs, Material rationalisation

1 INTRODUCTION

1.1 MOTIVATION

The worldwide CLT production is constantly growing. Especially in Europe the growth is remarkable with existing producers already building additional production lines and new players entering the market (Figure 1). As the demand for CLT is growing so is the price of timber. The price of spruce and pine (logs) over the last 15 years has been increasing. On the other hand, the price of beech has been decreasing as shown in figure 2 for the case of Germany. A logical consequence of this could be to incorporate more beech (or potentially other hardwoods) in CLT production. There has been a lot of research dedicated to this subject in the recent years.

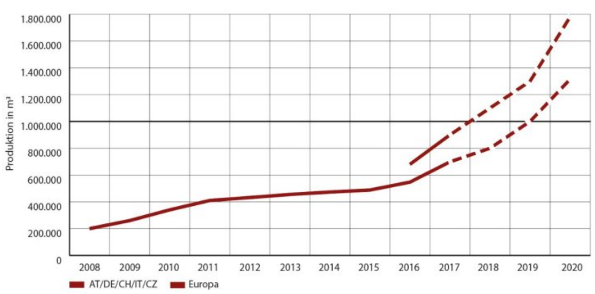

Figure 1: *European CLT production [1]*

However, there are still several obstacles to be overcome before. Hardwood production differs from softwoods, CLT factories would need to be substantially modified to allow its use. Hence for the time being the answer to more rational CLT systems lies elsewhere.

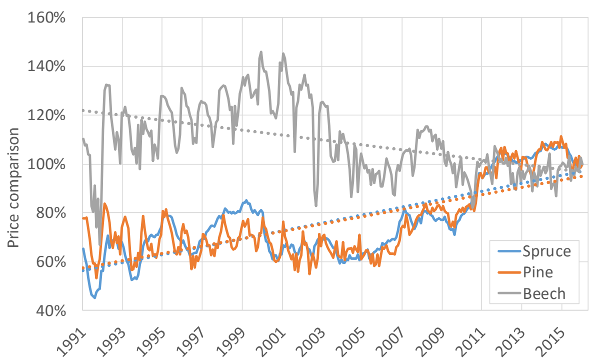

Figure 2: *Spruce, pine and beech log prices in Germany, benchmarked to 2016 prices (data source: Federal Statistical Office, Germany)*

The main objective of the new CLT plates proposed in this paper is to optimise the structural performance of regular CLT in terms of material use by thinning the plates and incorporating the ribs into the main panel's structure as demonstrated in figure 3.

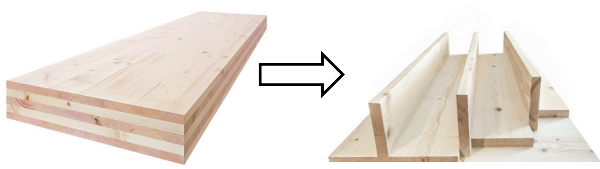

Figure 3: *Transition from a massive to ribbed CLT structure*

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1.2 RIB INTEGRATION CONCEPT

The ribbed plate's production process, namely lamella assembling, gluing and pressing is performed in one step. Pressure is applied from both vertical and horizontal sides (Figure 4) which ensures a stable and robust joint between the ribs and the slab. It also allows the use of standard lamellas for all components of the ribbed plate. The slender lamellas are straightened during the side pressing; something that is very difficult to achieve if the lamellas are glued separately on a regular CLT plate.

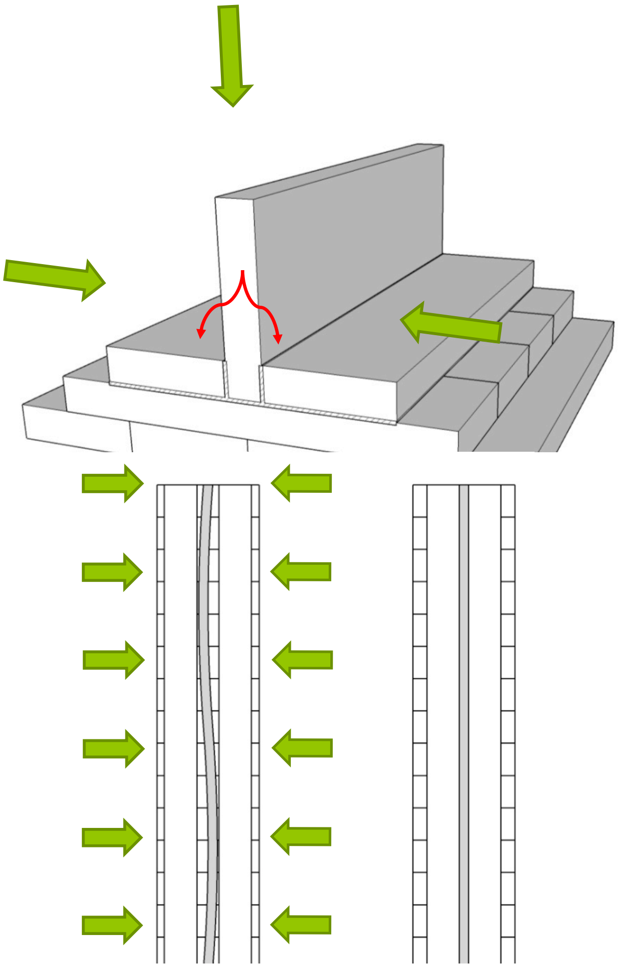

Figure 4: *Bi-axial pressing*

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 longer spans. These elements are larger with ribs usually made from glulam and CLT plate thickness of 10 cm or more. The newly proposed XR-lam plates, however, are designed to bridge spans where standard CLT is still used (up to 8 m) easier, without unnecessary cost and material consumption. The second main field of the XR-lam plate use is for walls with ribs on the outer side of cross-laminated timber panels 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. 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.

1.3 CROSS SECTION OPTIMISATION

The spacing between the ribs was determined based on the possibilities the production press could have without being too complex and hence too expensive to produce as well as maintain. Therefor (Figure 5) a 100 mm and 200 mm spacing was chosen with an additional 625 mm distance for cladding sheet optimisation (i.e. hard insulation plates on the façade). The rib thickness was 20-40 mm. The rib height is bound by the timber lamella dimensions which are in most cases up to 240 mm (in no case more than 280 mm). Hence the rib portion protruding outside of the plate can be up to 220 mm. For the testing specimens, it was limited to 180 mm. Individual layers of the massive part of the ribbed plate are 20-40 mm thick which is already common with some of the regular CLT producers.

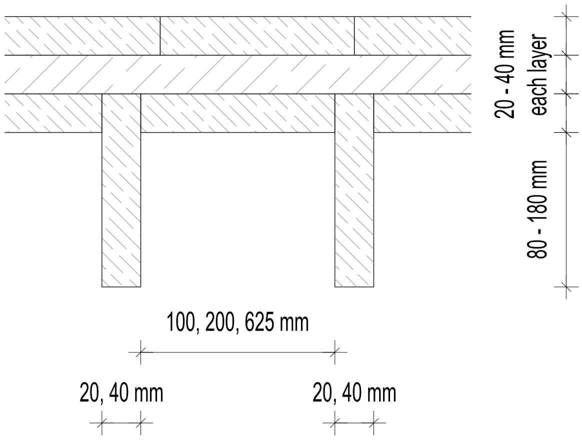

Figure 5: *The XR-lam plate geometries selected for specimen production and testing*

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, though, 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 [2] the compression timber plate of 120 mm thickness suffices, regardless of the rib dimensions. However, 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.

2 TEST SPECIMEN 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 which filled the voids between the ribs. The dummies were planed to exact height to establish a flat pressing surface on top of the specimen.

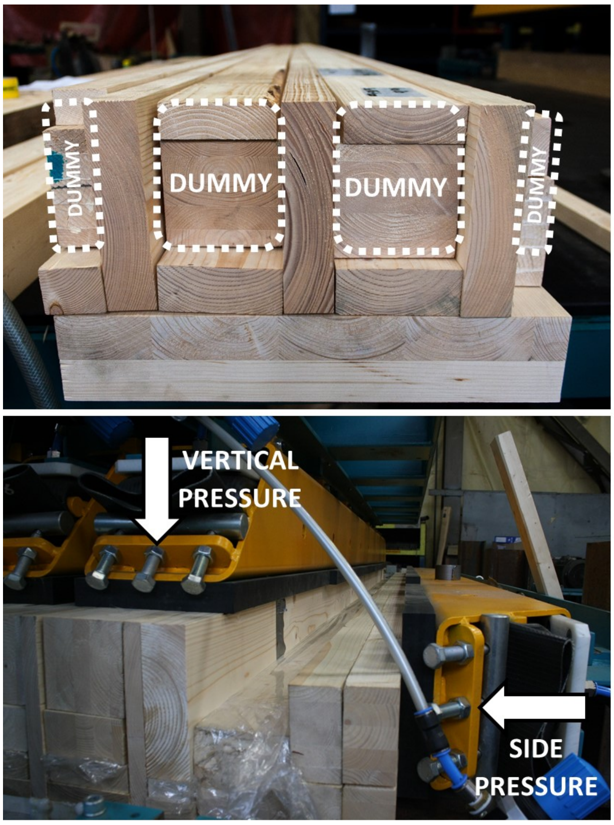

Figure 6: *The temporary dummy elements used for pressing the ribbed structure and the pressing production*

Over 40 floor and wall elements were produced altogether. Three different cross section geometries were chosen based on the boundary conditions described in the previous chapter. Some of the produced elements were comparison specimens made from regular CLT plates with ribs glued directly onto them with a special stabilisation system. Most of the elements were intended for four-point bending testing according to standard EN 408:2010 [3] performed on elements with 2 and 4 metre spans (as shown in figure 7). Apart from floor elements, also wall segments were made with a wider (62.5 cm) rib spacing. These wall elements were tested for buckling strength and stability.

3 EXPERIMENTAL TESTING

3.1 OUT-OF-PLANE BENDING

The experimental test program was carried out at MPA Otto Graf institute. It was focused on in-plane bending tests of ribbed timber slabs and vertical compression tests of wall elements. Some of the plates were tested for bending with the ribs facing down, some with ribs facing up. Two lengths of each geometry setup were tested to provoke either bending or shear failure in the elements.

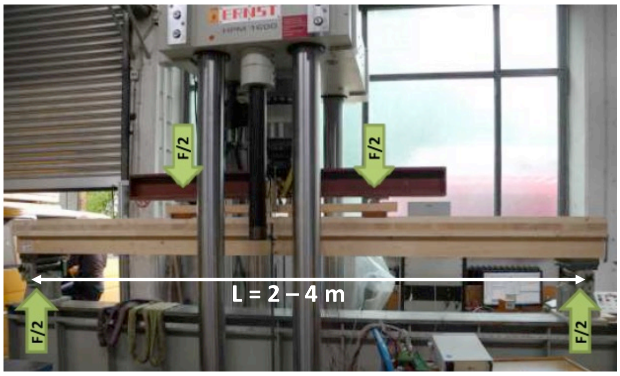

Figure 7: *The 4-point bending setup*

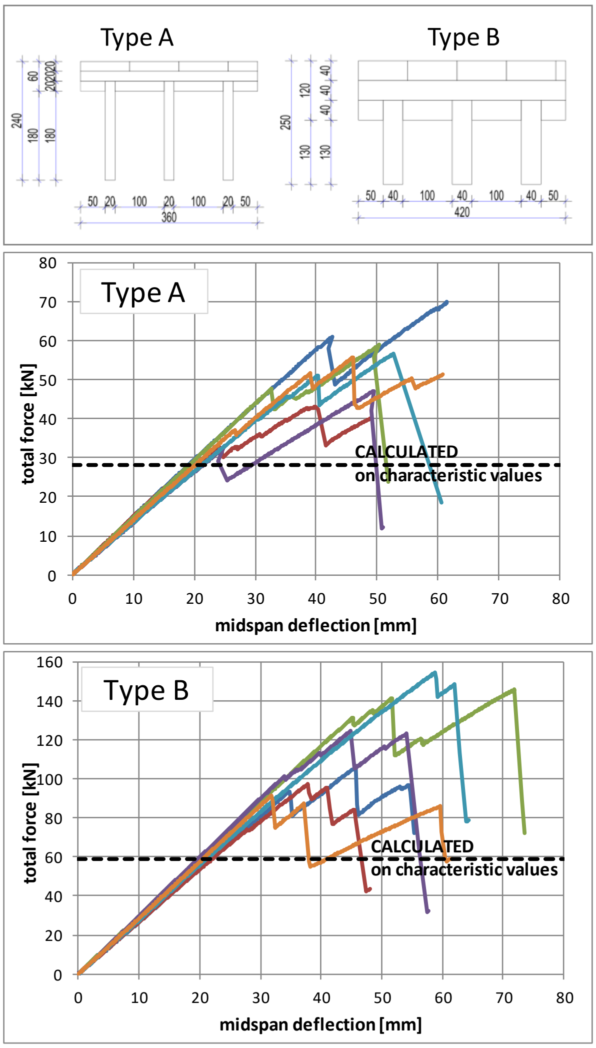

Figure 8: *Load displacement curves and damage development for ribbed plates in out-of-plane bending*

The testing had shown that the ribbed plates exhibit an almost ductile behaviour in out-of-plate bending with damage occurring progressively. Namely, after the first damage (bending or shear) develops in one of the ribs, the force is then redistributed to other ribs. After an initial drop, the force starts to climb again until new damage occurs and so forth. Until the final failure of the last element (rib). The "zig-zag" load displacement curves are shown for two different cross sections on 4 metre spans in figure 8.

3.2 HARDWOOD RIBS

Three additional specimens were also made with different rib types (figure 9); namely solid beech, LVL and combined LVL (the most stressed part made from LVL, the rest from spruce). These elements were tested on 4 m spans with the ribs turned upwards and stabilised against lateral torsional buckling in the middle of the span (where the vertical load was introduced).

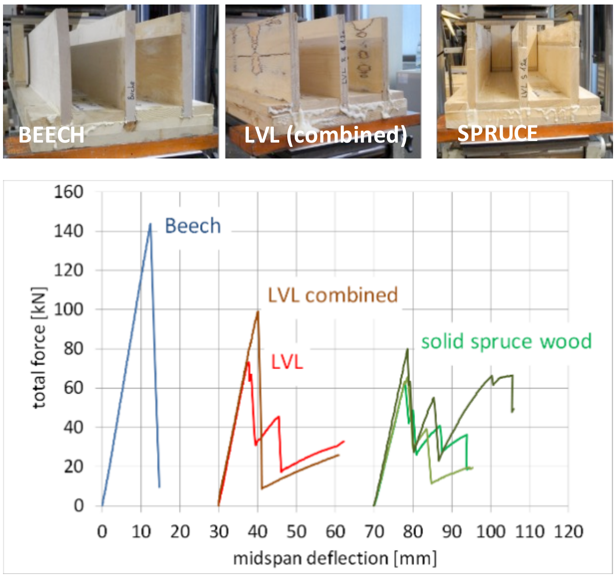

Figure 9: *Results of different types of ribs*

The results show the potential of beech ribs as the (single) specimen showed an almost double strength to that of spruce ribs. However, the beech rib specimen lost the ability to develop damage gradually; all three ribs failed simultaneously.

3.3 WALL COMPRESSION

The wall specimens, 2.95 m high and 1.25 m wide were tested for buckling (figure 10). 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.

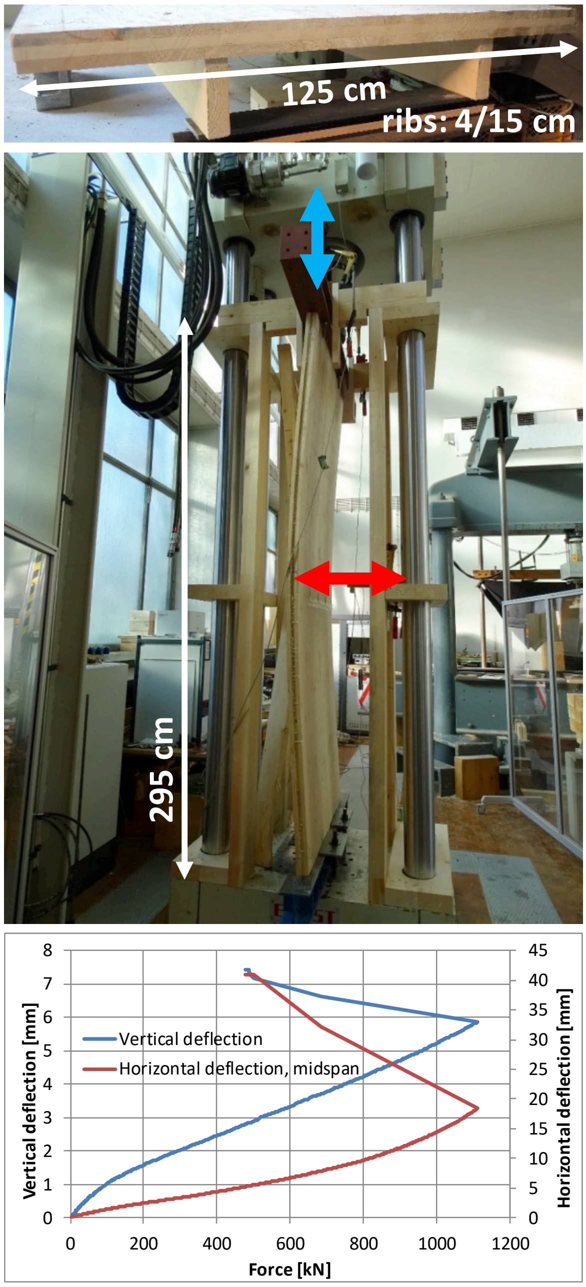

Figure 10: *Load displacement curves for walls under in-plane compression loading*

4 NUMERICAL SIMULATIONS

4.1 PROGRESSIVE DAMAGE FEM

A 3-dimensional finite element (FE) model was created using the ANSYS program package to calculate the load-deformation behaviour and the corresponding stresses and strains of ribbed plates during bending. In the case of FE models the symmetry conditions of the test arrangement were respectively utilized and, in the element longitudinal direction, only half the geometry was modelled. Symmetry conditions have been established in element centres. With regard to the width direction of the rib elements, the second symmetry, which would result from the symmetrical geometry of the three ribs, could not be applied because the later successive damage was generally not symmetrical and the associated asymmetrical load transfer effects were investigated. An eight-nodular cuboid element

(SOLID185) was used for the modelling of both the rib element and the bearing plates. The bearing condition at the load introduction was modelled by means of a contact element (CONTA173), which is provided for a 4-knotted surface-to-surface contact. The load was introduced as a surface load on a part of the compression plate and corresponded to the experimental load. The pivoting and sliding supports, experimentally achieved by using rollers under the bearing plates, were also modelled in the FEM. A linear elastic material law was assumed for each calculation step. The anisotropy of the wood was approximated by orthotropic material parameters.

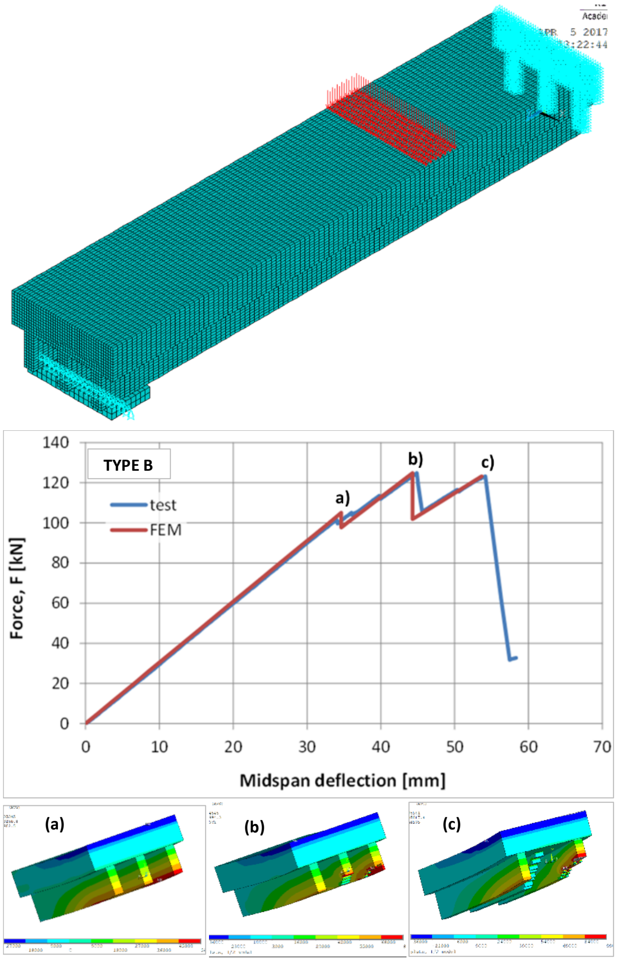

Figure 11: *A combined 3D finite element model follows the gradual damage development*

The selection and assignment of the material properties were carried out as follows; a separate set of orthotropic material parameters was used for the plate and the individual ribs. Different values of the modulus of elasticity parallel to the fibre direction were assigned to different parts of the cross section. All other stiffness characteristics, i.e. the elastic moduli perpendicular to the fibre direction and the shear moduli were derived in accordance with the relationships defined in EN 384 [5]. The Poisson coefficients were taken from literature without further adjustment. For the compression plate, a nominal value of the elastic modulus was set parallel to the main direction using data for a three-layered plate provided by StoraEnso. The individual E-modulus values of the ribs were taken from the test results of the material characterization and assigned to individual elements. Thus, for each element, a separate material data set was available, which was applied for the respective modelling of the individual rib elements.

During the simulation of individual experiments, the damage behaviour was simulated as follows, despite the restrictions of the linear elastic material approach. The first predominantly linear part of the recorded load-deformation was approximated by the full linear model. If there were deviations between the measured and the modelled stiffness due to the missing exact data of the compression plate, a compensation factor was used with values between 0.8 and 1.1. In the following steps the successive load-deformation segments were calculated by a further linear-elastic simulation after the experimentally found damage was simulated by interventions to the model. For example, a part of the FE network was cleared in the damage zone. For shear fracture the connection between a few nodes in the shear plane were released, hence a shear crack was simulated. The respective sections of the linear curves were then connected to one another at the respective peak points so that the resulting curve could be directly compared with the experimental results. A case of the complete backbone is shown in figure 11.

4.2 SIMPLIFYED LINEAR MODELS

Simplified models suitable for building code implementation were derived based on the element's cross sections. Using such models, a wider parametric study was performed to assess the performance of ribbed Xlam compared to conventional CLT and evaluate the potential reduction of timber used to achieve equal performance. In figure 12 a comparison of timber consumption between regular and the new ribbed Xlam is shown for 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 were checked (and turned out to be 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 were assumed to be of C24 strength class [6]. The study shows that Xlam ribbed plates could be using 25-50 % less of timber to achieve the same effect. The difference in material consumption is smaller for larger spans. It must be noted that the overall cross section height of the ribbed plates is 20-90% higher. Nevertheless, the space is not lost as 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.

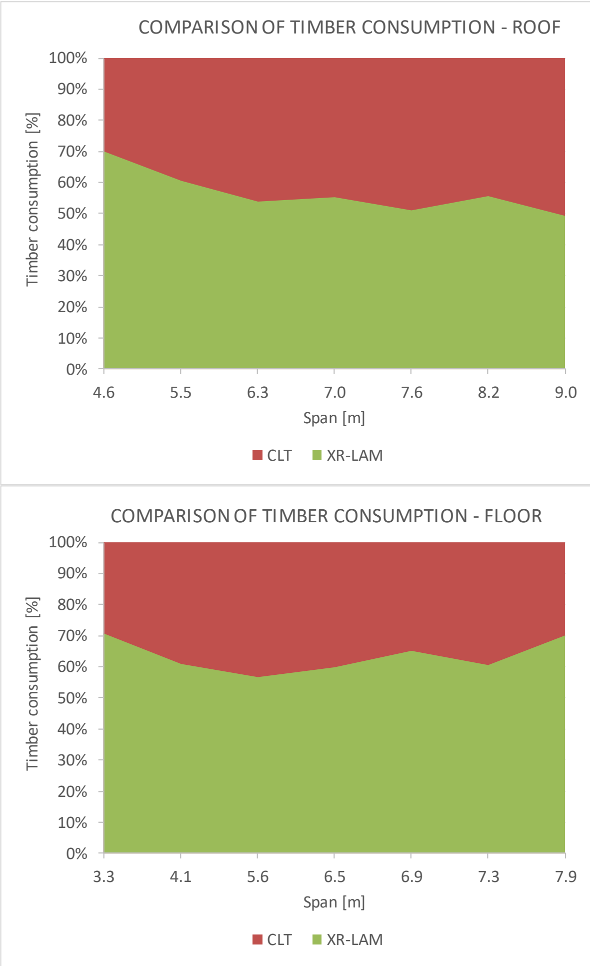

Figure 12: *Comparison of timber use for floor and roof elements for conventional and ribbed CLT plates if calculated according to material characteristic values*

5 FULL PRODUCTION LINE

A full production line concept was developed. The fully automated production line, with a capacity of 300 000 m^2/year, ensures the new element production costs remain practically equal to conventional CLT.

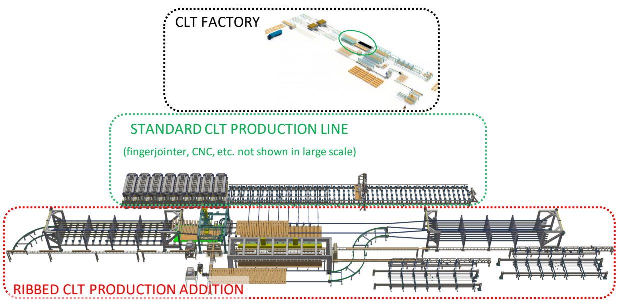

Figure 13: *The XR-lam plate full industrial production line*

The line allows the production of both standard and ribbed CLT since the machinery for adding ribs is conceived as an addition to a standard line. It can hence also be installed as a modification to existing CLT productions.

6 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. If beech ribs were used the bending strength of the element doubled compered to spruce ribs, however such elements failed in a brittle manner with all the ribs breaking simultaneously. The ribbed wall elements had demonstrated a high vertical load bearing capacity. Overall the elements present an interesting alternative to conventional crosslam with their lower timber consumption and a lesser impact on the environment on the one hand and competitive production costs on the other hand.

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