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HYBRID CROSS-LAMINATED TIMBER PLATES (HCLTP) – NUMERICAL OPTIMISATION MODELLING AND EXPERIMENTAL TESTS

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ABSTRACT: This paper presents the development of two new types of hybrid cross-laminated timber plates (HCLTP) with an aim to improve structural performance of existing cross-laminated timber plates (Xlam or CLT). The first type are Xlam plates with glued timber ribs and the second type are Xlam plates with a concrete topping. A numerical optimisation was performed to study optimal plate setups in terms of ultimate limit state and serviceability limit state requirements. The numerical outcomes served as input for defining the specimens for experimental tests on subassemblies and full-scale specimens. The new elements in general show improved structural performance with less material used. Experimental and numerical investigations serve as essential information for further extensive parametric studies of hybrid cross-laminated timer plates and development of design models and principles for implementation in the building codes.

KEYWORDS: Cross-laminated timber, Hybrid plates, Experimental tests, Numerical modelling, Optimisation

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 two new hybrid types of cross-laminated timber plates (HCLTP) that address these issues. The first type is the so called “Xlam ribbed plate”, with timber ribs glued within the Xlam plate’s structure. The second type of modified Xlam plates have a layer of concrete attached on Xlam plate in various manners. The main objective of the newly proposed hybrid Xlam plates is to optimise the structural performance of regular Xlam in terms of optimisation of material use. In addition, also other cost-reduction improvements can be achieved. Namely speeding up of the construction process as final building layers (insulation, façade etc.) can be installed easier and material for an additional sub-façade structure is not needed any more. As such they could present a more competitive and forest friendly product on the market.

2 HYBRID CLT PLATES

2.1 XLAM RIBBED PLATES

There is a high demand for the ribbed-type plates on the construction market. The main use of such plates is for floor and roof panels with higher stiffness and strength for larger spans (Figure 1, Figure 2).

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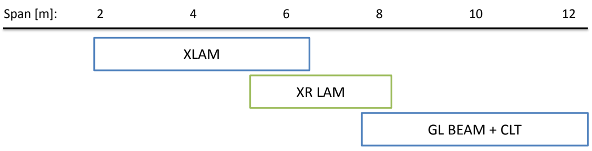


Figure 1: *The target span area for the new Xlam-ribbed (XR-LAM) plates*

The second main field of their use is for walls with ribs on the outer side of cross-laminated timber walls that serve as a sub-construction for insulation and a façade. In addition, ribbed wall elements would allow for higher buckling resistance with the façade sub-structure being included in the main product. Hence such elements would ensure a more effective construction with lower timber consumption for equal loads and at lower production costs.

Figure 2: *A basic Xlam ribbed plate structure and various rib combinations*

Combining Xlam and glue-laminated or massive timber beams into a ribbed-type is currently in practice performed as a two-step process. This means additional plate and rib manipulation that can also demand the 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 due to the secure positioning in their stable cover layer structure.

2.2 XLAM CONCRETE PLATE

The second proposed hybrid Xlam plate type is a combination of Xlam plates with a concrete top or bottom layer. A combination of concrete and timber is sometimes used for strengthening existing older timber joists [2] by pouring concrete slab over the joists and forming a composite structure with massive timber ribs and a compression concrete slab. Steel shear bolts are used for the shear force transfer from timber to concrete. The newly proposed product uses a similar principle, however in a hybrid plate form and with different connecting principles.

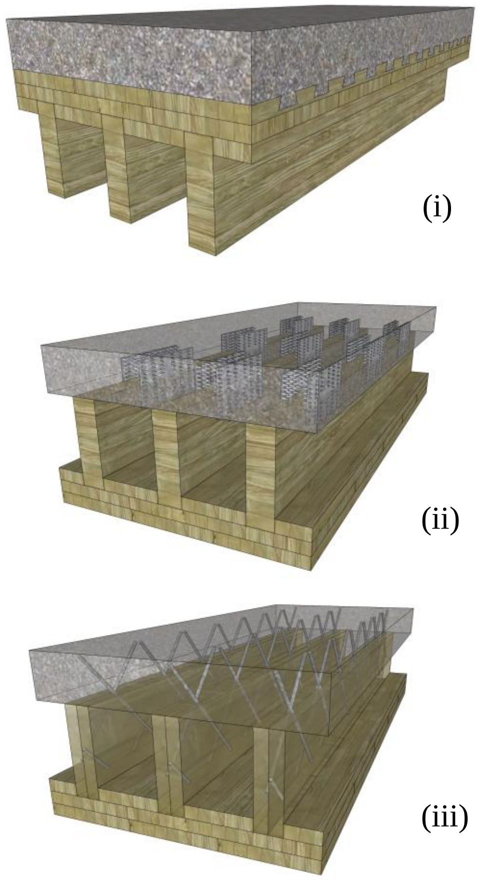


Figure 3: *Planned timber-concrete specimen types*

The benefits of such a plate are its higher stiffness and strength, its versatility and adaptability to various boundary conditions. If concrete is used as a bottom layer (with reinforcement) higher strength and stiffness are also complemented with a fire protection layer. The concrete layer can also be useful for ensuring stiff floor membrane behaviour during seismic events (as commonly demanded by seismic design standards). The concrete can be poured in the factory, hence making the plates completely prefabricated or at the construction site, consequently tying them all together and forming a floor membrane.

The top of the first type of a concrete-timber cross laminated plate (Figure 3i) is formed in the final shape during their production, by either cutting grooves in the final layer of lamellas or spacing them further apart and using the necessary thickness of boards to ensure an optimal shear force transfer. The second type (Figure 3ii) connects the concrete layer with the timber ribs over nailed plates and the third type (Figure 3iii) over a standard reinforcement mesh that is pressed between two lamellas that serve as a rib element in the plate's structure.

3 NUMERICAL OPTIMISATION MODELLING

Development of finite element models (FEM) of the proposed hybrid Xlam plates and walls served to find out the 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 variable combinations with the least material used while still being within pre-defined realistic dimensions.

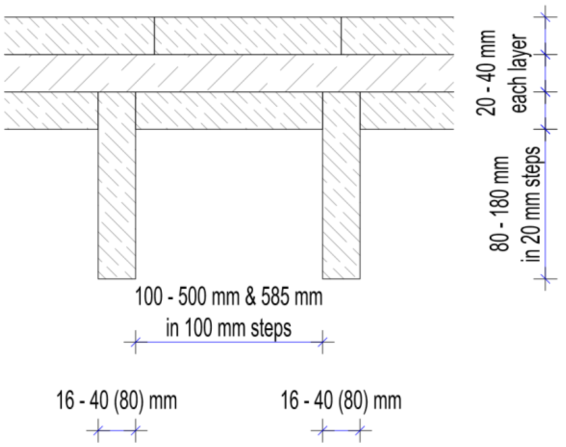
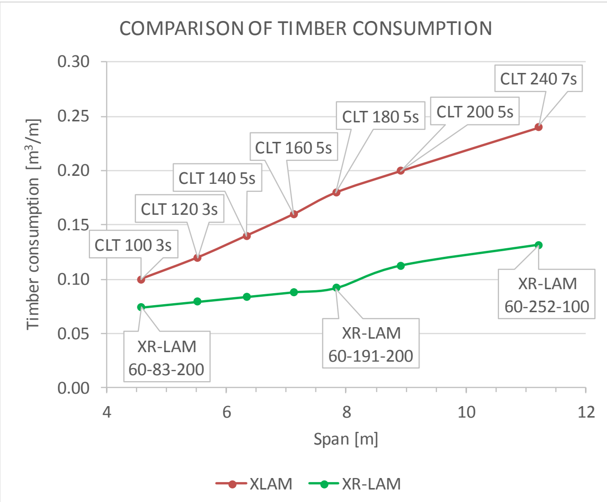


Figure 4: *The ribbed-Xlam plate geometries selected for further production development and testing*

However 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 the most efficient in terms of material use. The spacing between the ribs was 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 to 500 mm spacing was chosen with an additional 585 mm distance for cladding sheet optimisation (i.e. hard insulation plates on the façade). The desired rib thickness is 16-40 mm with an option of 80 mm for a higher fire protection. The rib height is bound by the timber lamella dimensions which are in most cases up to 200 mm. Hence the rib portion protruding outside of the plate can be up to 180 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 Xlam 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 effects. The three-layer setup still offers all the benefits of regular Xlam (high in-plane stiffness, robustness etc.) yet takes full advantage of the ribs.

In the following figure (Figure 5) a comparison of timber consumption between regular and the new ribbed Xlam is performed on a single span roof element (self-weight of the plates + additional dead load of 1,0 kN/m^2 and snow load of 1,5 kN/m^2, combined with factors 1.35 and 1.5 respectively for ULS and both with 1.0 for SLS). Only stresses and displacements were taken into account, whereas for the floor elements also vibrations would need to be checked. The ribbed Xlam (XR-LAM) elements labels present the plate thickness – rib lamella height – rib spacing. Therefor XR-LAM 60-191-200 means a ribbed plate with a 60 mm (20-20-20) thick 3-layer plate and 191 mm high ribs (part protruding from the plate) spaced at 200 mm centre-to-centre. In all cases the ribs are assumed 40 mm wide. It should be noted, however, that the rib heights in this study do not absolutely comply with the boundary conditions set in Figure 4. In some of the setups in Figure 5 the rib lamellas should be over 200 mm high.



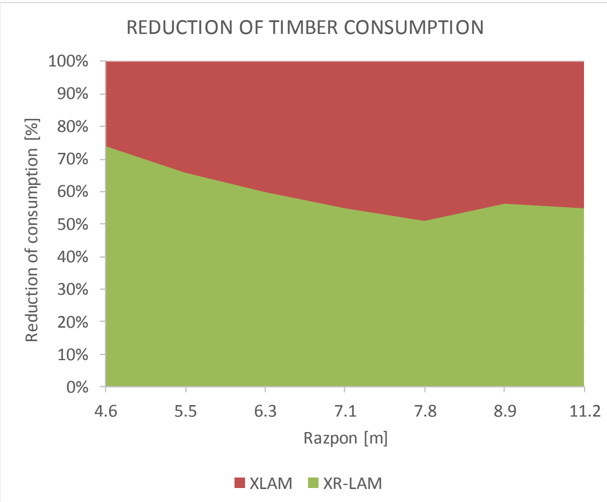


Figure 5: *Comparison of timber consumption of Xlam ribbed plates compared to regular cross laminated timber plates*

The aforementioned study shows that Xlam ribbed plates could save 25-50 % of timber to achieve the same effect with the optimum efficiency at a span of about 7.8 m.

4 SMALL SCALE RIB PUSHOUT TESTS

The key feature to achieve the full load bearing capacity of ribbed Xlam plates is a high capacity glued connection between (Figure 6) the massive part of the plate and the ribs. In simple numerical models it theoretically makes no difference if the rib is only glued to the plate with its narrow side and no side gluing is used. However, the side pressing and side gluing bring several benefits. They enable the use of high and narrow lamellas which provided the most efficient cross sections in the numerical optimisation study. In addition, the rib-lamellas do not have to be absolutely perfectly straight as the side pressure straightens them. Although probably the most important benefit comes in the form of robust production and later also manipulation with the elements if the ribs are pressed and glued in the structure from all sides. In order to experimentally investigate the effect of side gluing, rib and side lamella thickness as well as material properties (sawn timber, oriented strand board – OSB) a series of rib pushout tests was performed according to the shear strength testing guidelines of standard EN 408:2010 [3].

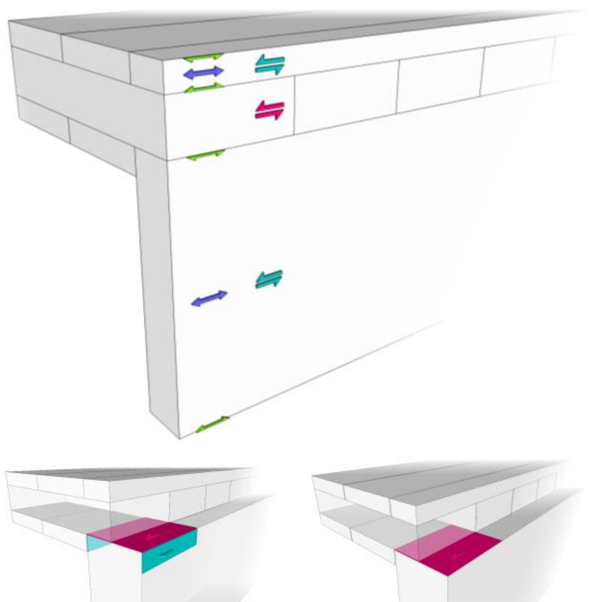


Figure 6: *Normal and shear stresses in a cross section along a rib at bending; the areas of rib gluing are highlighted.*

A matrix of boundary condition interactions is presented in Figure 7. Namely 9 different setups were tested with 3-4 samples each. Ribs were made of 20 and 40 mm thick massive timber lamellas (grade C24 according to EN 338:2003 [4]) as well as 12 mm thick OSB plates. Side lamellas were made from 20 and 40 mm thick massive timber lamellas (C24). The effect of side gluing was studied.

The specimens were made with the help of carpentry clamps (Figure 8) and a carpentry press. Altogether 29 specimens were made. The small T-sections were 300 m high and 140 x 140 mm in cross section. The steel clamping (Figure 9) was engineered to achieve a 14° angle demanded by the standard. Pivot joints were installed in the steel clamps. The ribs were protruding 1 cm out of the timber plates.

The testing was performed at the laboratory of the Biotechnical faculty of the University of Ljubljana using a 100 kN capacity Zwick Z100. Deformations or displacements were not measured as they are not expected to happen in the glued connection. Only the maximum shear force in the connection was being recorded.

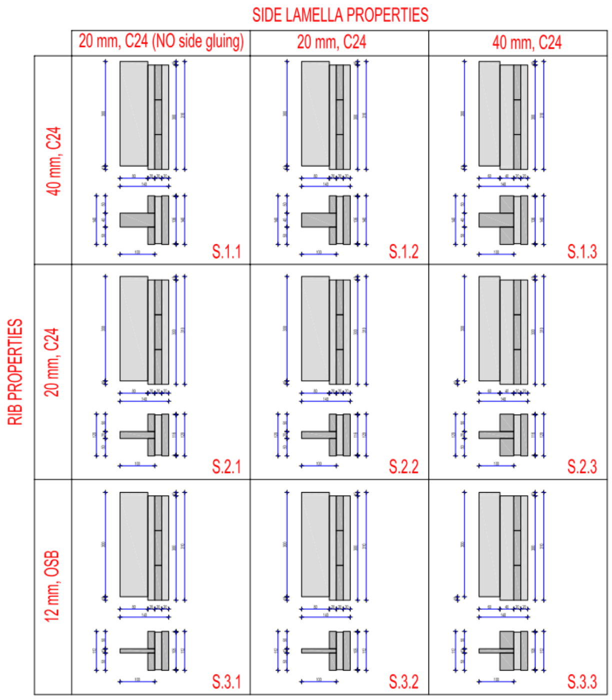


Figure 7: *The matrix of rib pushout specimens with different boundary conditions*

Figure 8: *Production of small-scale samples and final products*

The theoretical characteristic shear force in different specimens, calculated using the C24 [4] parallel to grain shear strength (f_v = 4.0 N/mm^2) in the glued joint and net timber rib area would be the following (Table 1).

Table 1: *Calculated characteristic and mean experimental values*

Specimen	$F_{v,k}$ (timber) [kN]	$F_{v,k}$ (glue) [kN]	$F_{exp,mean}$ [kN]
S.1.1	46.4	46.4	56
S.1.2	46.4	92.8	51
S.1.3	46.4	139.2	62
S.2.1	23.2	23.2	32
S.2.2	23.2	69.6	44
S.2.3	23.2	116	42
S.3.1	0.9	0.9	18
S.3.2	0.9	3.8	13
S.3.3	0.9	6.7	18

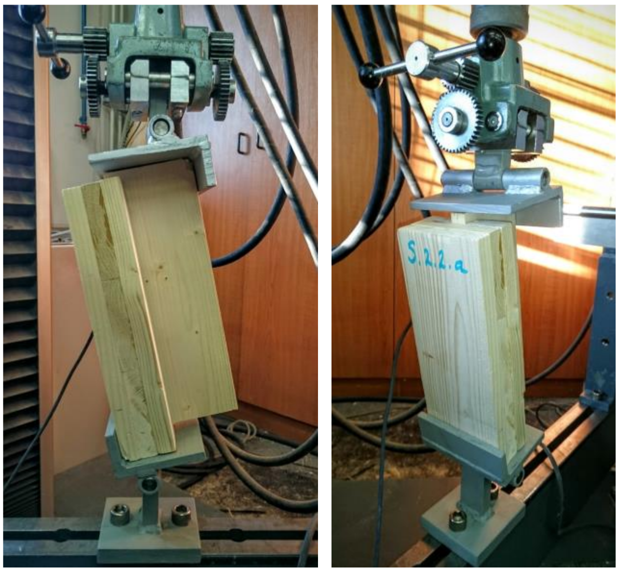


Figure 9: *Rib pushout testing under EN 408 boundary conditions*

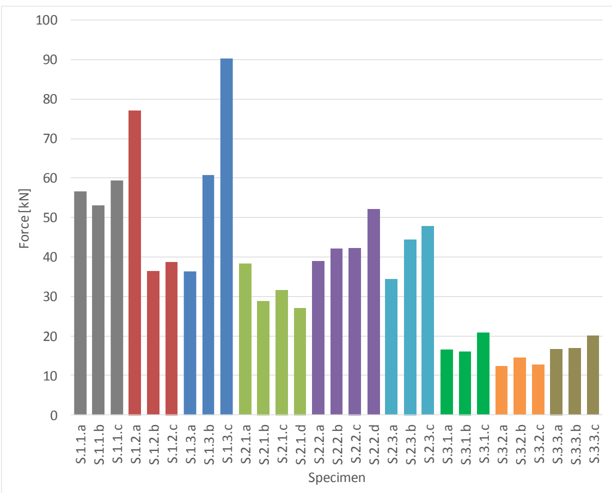


Figure 10: *Rib pushout test results*

The average mean values of experiments were about 20% higher than the characteristic values of net timber resistance. The small scale experiments have hence not directly shown (Figure 10) that side gluing is necessary, however the production process of specimens showed the necessity for side pressing and gluing that enables a more robust and reliable production. A lesson that was later transferred to the production process design.

5 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.

Figure 11: *Large specimen production; vertical pressing over dummy elements and side pressing*

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 actually 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 11). The vertical pressing was established with the help of dummy elements to fill the voids between the ribs. The dummies were planed to the exact height in order to establish a flat pressing surface on top of the specimen.

Figure 12: *One of the final specimens*

Over 40 floor and wall elements (Figure 12) were produced. Some of them being comparison specimens made from regular Xlam plates with ribs glued directly onto them. Their performance will be analysed and compared against the new ribbed elements from the aspects of load-bearing performance and robustness.
The glue-lines (Figure 13) established during production were kept below 0.2 mm according to the demands for polyurethane adhesives.

Figure 13: *Glue lines; thickness is kept within allowable tolerances*

Also timber-concrete elements were produced (for the time being without the concrete layer), however the specimen in Figure 3iii had to be cancelled. Namely the pressing of a reinforcement mesh into timber demanded too much force for the press available. Small scale specimens proved to work well (Figure 14), timber crushing and damage was kept very local. The steel reinforcement bars (6 mm) were pressed, the timber boards were not splitting. The pressure perpendicular to grain in this case, however, was approaching 6 N/mm^2, over double the characteristic value of C24 grade timber. Small scale push-out tests will still be carried out though as the proposed system could perhaps later be used with either an adhesive with added filler (epoxy based) or a stronger press could be used.

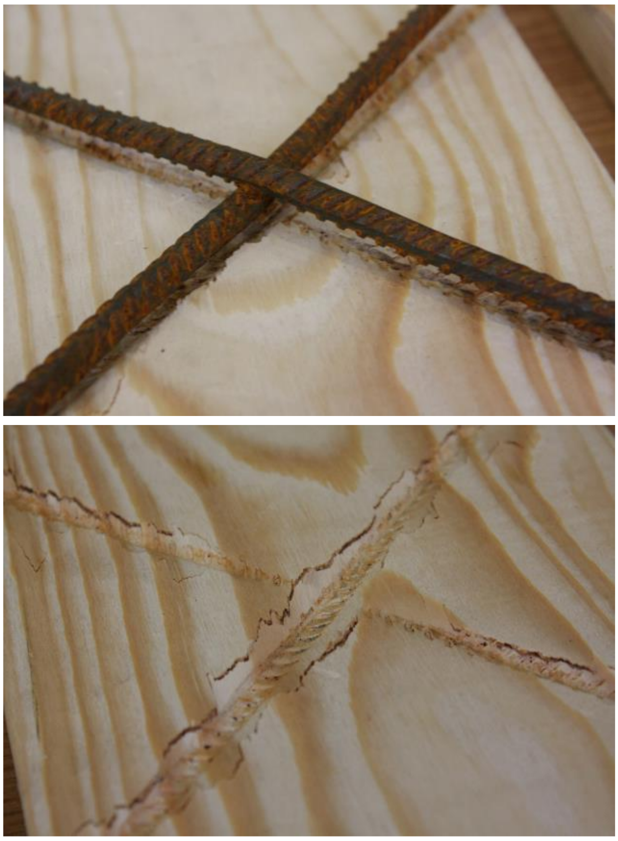


Figure 14: A t*imber-concrete system rib with a pressed-in reinforcement mesh*

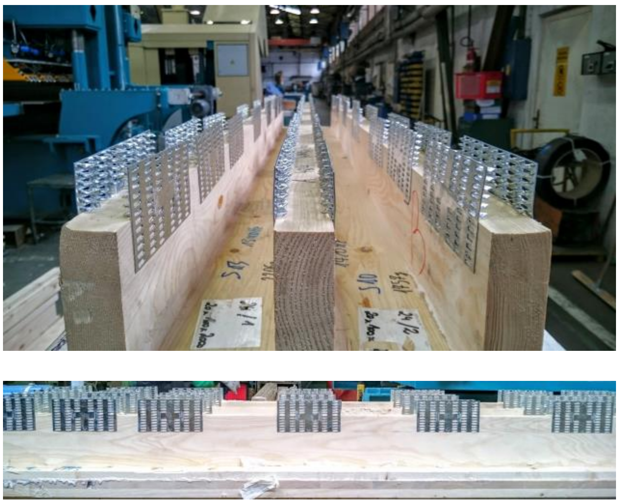


Figure 15: A *timber-concrete base plate with nailed plates for connecting the two materials*

The nailed plate specimens (Figure 15) on the other hand proved to work well. The nailed plates were pneumatically pressed into the ribs and adapted dummy elements were used to press the whole element together. Nailed plate spacing was adjusted so more plates are present and specimen ends where the shear transfer forces are the highest.

6 LARGE SCALE BENDING AND BUCKLING TESTS

An experimental test program at MPA Otto Graf institute of prototype setups will be focused on in-plane bending tests of ribbed timber slabs and vertical buckling tests of hybrid Xlam wall elements. Out-of-plane 4-point bending tests will be performed according to standard EN 408:2010 [3] (Figure 16).

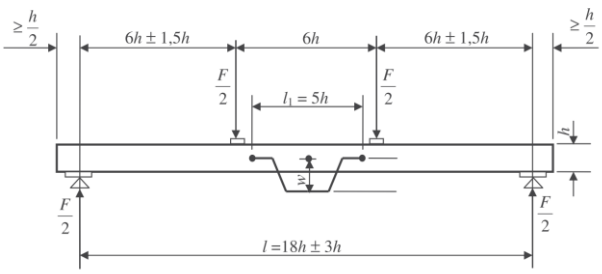


Figure 16: *The four point bending test according to EN 408*

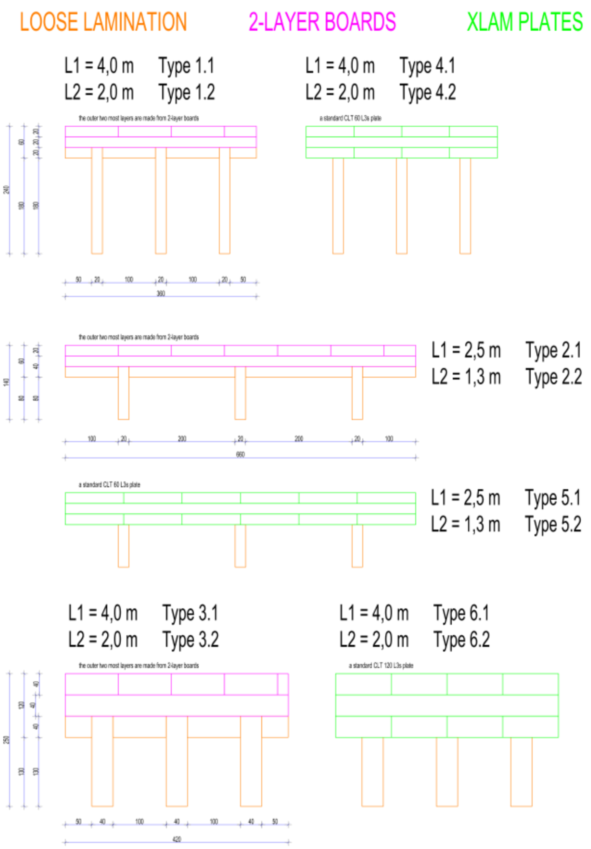


Figure 17: *The main geometries of large scale specimens intended for four-point bending tests*

The plates will be tested for bending with the ribs facing down. Effective widths of the ribbed cross laminated plates' massive slabs will be measured by shear deformation lag in the slab plane. Two lengths of each geometry setup (Figure 17) are planned to provoke either bending or shear failure in the elements. Vibration modes will also be measured to enable later studies of vibration which is often the governing criteria in floor design.
Vertical stressing of plates will be performed in order to achieve a buckling failure of wall elements (3 m high and 1.25 m wide.

7 ADITIONAL ANALYSES

The research is also focused on the building physic, architectural detailing and technical approval procedures necessary for the elements to be overall technically supported.
The main properties with regard to building physics of the most promising conceptual designs for floor and wall elements are being developed and analyzed. The properties for building physics parameters of the system, i.e. thermal insulation and storage capacity, humidity transport, and noise insulation, are being identified by explorative testing. These investigations are complemented by further results of numerical simulations.
Two different kind of simulations are being accomplished. One regarding the impact of the heat storage capacity of the surrounding constructions to the operative temperatures of rooms, as well as to the heating energy demand. Additionally, to this thermal dynamic building simulation various construction based 2D hygrothermal simulations are done to examine the performance and durability of the construction also in respect to the hygric behavior.
A conditioned space of simple geometry surrounded by hybrid plates is compared to the same space bordered by solid and lightweight constructions - with regard to heating demand, as well as to summerly overheating hours. The simulation model measures 8 by 8 meters and 3 meters in height using external dimensions (Figure 18)

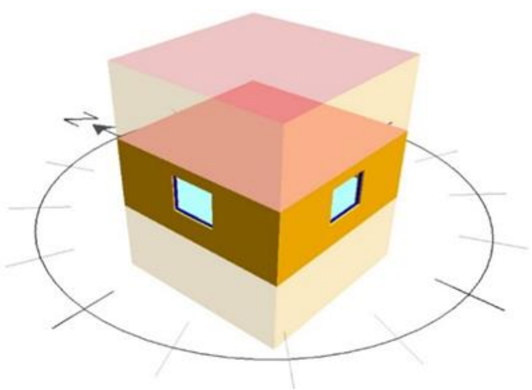


Figure 18: Thermal dynamic building simulation model

The room size is chosen referring to the possible span of the hybrid plates floor, which is 8 meters. The walls are exposed to external climate conditions, the floor and the walls are modeled as adiabatic borders, which means that the adjoining rooms below and above have same thermal conditions like the investigated room itself. The windows do not have any sunblinds, because if used, the summerly overheating hours could be reduced to zero (especially using the massive constructions) resulting in losing this value for comparison of the different constructions. The slabs are dimensioned to the corresponding span.

8 CONCLUSIONS

The optimised ribbed cross laminated timber elements are the most effective if narrow and high rib elements are used where up to 50% of timber can be saved compared to conventional Xlam.

The side pressing of elements is crucial if a stable and robust cross section is to be achieved with even the narrow ribs being glued reliably in the structure. The simple one sided gluing theoretically (and to a certain extent also practically) offers enough shear strength to enable the shear stress transfer, however the question of safe manipulation with the elements remains open in this case.

The timber-concrete specimens with pressed in reinforcement mesh turned out well for the smaller segments of the mesh, however would demand a stronger press to enable larger pieces to be pressed it. Also the compression strength of timber perpendicular to grain is very high when the mesh is fully pressed in.

Overall the numerical and experimental research performed so far has shown that the elements under development could have a competitive potential in the future market.

More information about the ongoing research is available on the website www.hcltp.com where the results of analyses and final reports will be fully published.

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