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CCLT – Development of a CLT based sandwich structure with bamboo rings as core materials

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ABSTRACT: This paper reports on early investigations for the improvment of conventional CLT structures. The massive timber consumption and resulting high weight of conventional CLT boards can be encountered by creating a sandwich structure using an alternative core material combined with timber top and bottom sheets. Therefore, a honeycomb core of bamboo rings called COMBOO is an option, currently under investigation. This approach was named CCLT (COMBOO Cross Laminated Timber) and can reduce timber consumption and weight via the hollow bamboo combs. After previously received interesting results from compression tests of bamboo rings themselves or bamboo rings with different top and bottom sheets and different bending tests with COMBOO and GFRP layers, the combination of the work with 4-point bending tests of the CCLT-structure is the content of this paper. A scaled approach with reduced height of the CCLT board has been chosen here. It contains manufacturing process descriptions and provides insight into the results from mechanical testing. During experiments it was found, that the bending strength depends on the number of layers and not on the bamboo ring size. The results of bending tests were promising but manufacturing of according components is yet difficult and requires the transfer to an industrial scale.

KEYWORDS: CLT, honey comb sandwich, lightweight composites, COMBOO, bamboo

1 – INTRODUCTION

Timber constructions play an important role in architecture and civil engineering as they provide significant benefits compared to steel and concrete structures.

Timber has been used as a building material throughout all time as it was widely accessible and could be easily machined with rather simple tools. However it´s been a long way from simple log houses to modern-day timber engineering, full of inventions and ideas. Whereas in the past the craftsmanship was decisive for the success of a challenging construction project, today complex computational tools, computer-aided prefabrication, and suitable joining systems alongside a “reproducible material” are the key factors .

Steel and concrete have their advantages which can’t be neglected, but their energy consumption during production is enormous. Another disadvantage is the huge amount of CO_2 released during production. CO_2 is deemed to be responsible for climate change.

Wood however requires and stores CO_2 during its growth, the amount of CO_2 bound depending on the species and speed of growth. Timber is a light weight compound (density e.g. 0.45 g/cm^3 for spruce as a typical building material), anisotropic and absorbs or releases water depending on the relative humidity which leads to either shrinking or swelling sometimes resulting in the deformation of simple beams or boards. Timber can be joined by connecting means like screws, dowels and glues forming large and sometimes highly complex structures with often beautiful appearance.

2 – BACKGROUND

This section describes the background of the research project, giving an overview of the conventinally used product, a brief description of a new approaches and our previous own work in this field.

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2.1 CLT

In civil engineering and architecture, working with timber constructions becomes more and more interesting especially for larger projects. Therefore new material combinations with suitable gluing systems and hence improved characteristics are required. The experiences from glulam were adopted and combined to form a layered material similar to plywood. Since the early 90s, the evaluation of the new material “Cross Laminated Timber” (CLT) or X-LAM took place. [1]

In CLT an uneven number of layers of parallely aligned timber boards are combined under a 90 degree rotation of each layer, comparable to plywood. The main advantage of this alignment is the dimensional stability of the resulting board. Each layer has a thickness usually between 6 and 45 mm. [2] The CLT boards have a final thickness from about 60 mm up to 500 mm with lengths of up to 30 meters and widths up to 7 meters, while about 3 x 13 meters are common due to transport restrictions. CLT boards are made of high quality timber mainly spruce and pine, sometimes combined with larch or swiss stone-pine for surface layers. Experiments with beech, birch, tulipwood and other deciduous trees can be found in literature. [3], [4]

Production of CLT mainly starts by carefully selecting the raw boards, planning and combining them by finger joints and aligning the required number next to each other adding glue followed by the next layer with an rotatet angle and so on. The CLT boards are pressed by pneumatic or hydraulic presses. Even tough this process normally occurs on a high industrial level by companies like KLH Massivholz GmbH (Austria), ZÜBLIN Timber GmbH (Germany), Stora Enso Timber AB (Sweden) or the Pfeifer Holding GmbH (Austria) mainly situated in middle and northern Europe, machinery for production at smaller scales is also available. After manufacturing the large boards they are CNC machined and transported to the construction site. Especially the CNC machining in combination with this quasi homogeneous material allows small dimensional tolerances, high accuracy and “ready to assemble” parts.

To form these CLT boards, a very large amount of high quality timber is required. Alternative strategies might be interesting to reduce or minimize the necessary amount of said wood. An interesting approach could be the usage of sandwich structures.

2.2 Sandwich structures

Sandwich structures play an important role in various engineering applications, particularly in transportation and construction, as they combine good mechanical properties with low weight. Those consist of top and bottom layers or face sheets, separated by a core material.

The face sheets bear the primary tensile or compressive stresses under bending loads, distribute local loads and sometimes offer protection to the mostly lighter core. Sheet metals, FRP (fibre reinforced polymers) and plywood were well-known representatives for a wide field of materials, chosen by application.

The core material primarily absorbs shear stresses and distributes loads between the face sheets. It ensures that the face sheets are not excessively stretched or compressed under bending loads, as it transfers shear forces between them. The core helps to absorb normal stresses (compression and tensile forces). While the face sheets primarily handle bending stresses, the core is designed to resist axial forces (compression and tension) caused by external loads.

The core contributes to the boards torsional rigidity by increasing the distance between the face sheets. This reduces twisting or torsion when the panel experiences rotational forces. A thicker core enhances bending stiffness and minimizes sagging under lateral loads. Finally, the core also contributes to the insulating properties of the sandwich board, depending on the material. It can provide thermal, acoustic, or vibrational insulation.

Typical core materials in mechanical engineering include polymer and metal foams, lightweight woods or honeycomb structures made of metals and synthetic materials e.g. polyethylene or aramid. In architecture, the carpenters trade and civil engineering, wood-based materials like particle or strandboards, with or without chambers and openings can be found. Honey comb structures from cardboard were common as a lightweight filler in furniture and doors. However, many of these materials are energy-intensive to produce or rely on non-renewable resources, others exhibit insufficient mechanical properties for applications with structural needs. [5]

A promising alternative for core materials is the use of bamboo, as described in the next two chapters.

2.2 Bamboo - a magnificant material

Bamboo is an extremely fast-growing, renewable resource with high CO_2 storage capacity and outstanding mechanical properties. The tensile strength reaches values of around 370 N/mm^2 and compressive strength was found to be more than 90 N/mm^2. [5], [6], [7], [8], [9]

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It is a grass plant instead of a tree with a comparable chemical composition even though long fibers form the structure. It is estimated that there are probably over 1.400 species of bamboo worldwide, classified into approximately 115 genera. It is native to all continents except Europe and Antarctica. Bamboo stems appear as a hollow column, divided by nodes. Its longitudinal growth reaches speeds of up to 1 m / day (total heights of up to 40 meters can be reached), whereas tree´s wood growth happens in both length and thickness at different rates. Bamboo takes approximately 5-7 years to reach harvest maturity, whereas the coniferous species commonly used in construction require up to 80 years. The surface of the bamboo column has a silky wax-like touch even though it is very hard. Density varies over the diameter, the outer region is harder than the inner part, another difference to classical wood. The average density of bamboo varies between 0.6 - 0.75 g/cm³, while construction timber shows values around 0.45 g/cm³. [7], [9]

Bamboo has been used for ages especially in Asia and South America as a building material, for furniture, cooking and as food. Nowadays bamboo becomes more and more popular in Northern America and Europe also, mainly as laminated tiles, chopping boards. An astonishing and consistently impressive application of bamboo is its use as scaffolding material in Asia, where it is even employed in skyscraper construction. Beams and larger boards can also be produced from bamboo, as stripes were cut out, decorticated, planed or grinded and glued together. Companies like Moso International B.V. produce and sell these engineered bamboo products. Bamboo´s fire resistance is deemed problematic for load bearing applications, as charred stripes tend to fall out and reveal new unburned surfaces. [10]

Somehow problematic from the viewpoint of the authors is the utilization factor for several applications of a highly modified bamboo product. Large parts of the raw material is lost, especially from the harder outer region, depending e.g. on the diameter of the column in combination with the size of the desired stripes. A new approach tries to overcome theses limitations and tries to implement a higher efficiency.

2.3 COMBOO – Bamboo in a honeycomb pattern

The COMBOO concept utilizes a honeycomb structure of bamboo rings for core material (Fig. 1), which has been combined previously by the authors with glass or natural fibers and a resin as face sheets to form a sandwich structure. [5] , [8]

Figure 1. Test specimen (COMBOO with glass / flax fibres) [14]

The bamboo column has to be cut into rings of specific length according to a required height. It is assumed to be vital to receive parallel faces of the bamboo rings, wich is a complex task. Nodes and deviations from straight growth complicate the sawing process. A surface preparation prior to the sawing step might improve the contact between the rings during gluing. The next step is aligning the rings in a honey comb pattern on the resin soaked face sheet material, like glass fibers. The second face side can be added after curing of the resin or directly after finishing the first side. Adding a flat plate like a sheet of glass with a weight on top of the sandwich secures position of the components and good contact between face sheets and core material during the curing process. A release agent on the cover plate is helpful.

This sandwich structure offers high bending and compressive strength as well as good thermal insulation properties. [5], [11]

Another interesting difference of these honey comb pattern compared to massive bamboo lies in its density. Massive bamboo as a full material has a density nearly twice as high as the CLTs pine wood. The density of the COMBOO structure is a combination of bamboo and a big proportion of air in the rings. About two thirds consists of entrapped air, resulting in good insulation and lower weight. Density was calculated to be 0.2 - 0.25 g/cm³ depending on ring size, ring size distribution and ratio of inner and outer bamboo diameter.

Compared to traditional bamboo applications, such as the production of cutting boards, furniture, or laminates, the sandwich structure enables a more efficient use of the raw material. Additionally, new developments in the field of ecological resins and natural fiber composites will open up further possibilities for reducing the ecological footprint. The aim of this paper is to examine the mechanical properties of this innovative sandwich

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structure when combined with timber boards as top and bottom sheets, forming a CLT with a honey comb core from bamboo. The project name is CCLT for COMBOO Cross Laminated Timber.

3 – PROJECT DESCRIPTION

A funded research project looks into the potential of aforementioned CCLT sandwich structures for usage in civil engineering and architecture. The main idea is to substitute the large amount of timber used in conventional CLT by bambbo rings to save timber, thereby allowing lower transport weights and improving heat transfer. Mechanical properties like the bending strength of these sandwiches are desired to be similar to the original material.

As initially demonstrated, sandwich assemblies with face layers made of glass fibers or thin plywood have until now only been manufactured and tested in lengths up to 250 mm. That was improved in a first step to lengths of up to 1000 mm using wooden (CLT) face layers. The influence of the change in dimensions and the use of alternative adhesives on the manufacturing process will therefore be investigated on a model scale in order to obtain data for further scaling up to full-size CLT dimensions.

First it was decided to create CLT boards at a model scale with 3 and 5 layers and a height of 50 mm for comparison. Pine boards with a thickness of 27 mm were dryed and planed in the universitys carpenter workshop to the desired thickness between 10 and 20 mm. Table 1 shows the dimension figures of the test boards used.

Table 1: Dimensions of scaled CLT / CCLT boards

Test specimen
5 Layer
CLT 50 (10 - 10 - 10 - 10 - 10)
CCLT 50 (10 - 10 - 10 Bamboo d 40 - 10 - 10)
CCLT 50 (10 - 10 - 10 Bamboo d 80 - 10 - 10)
3 Layer
CLT 50 (15 - 20 - 15)
CLT 50 (15 - 20 Bamboo d 40 - 15)
CLT 50 (15 - 20 Bamboo d 80 - 15)

It was decided to join the boards of each timber layer to improve handling, especially for the 3 layered boards with COMBOO core later on. Here a Lamello biscuit joiner (Lamello AG Joining Technology, Switzerland) with biscuits has been used. The three biscuits between two boards were secured with 1 component polyurethane (PU) glue OTTOCOLL® P84 (Hermann Otto GmbH, Germany). That way boards the size of 1100 x 1100 x 50 mm have been prepared.

In the next step these single layer boards were combined to 3 or 5 layers of timber. The pressure necessary was applied by a concrete plate with a weight of 1584 kg and additional sandsacks (15 x 25 kg) on top of it. This resulted in a local pressure of $p = 0{,}02\ N/mm^2$ which is 40 times lower than the glue manufacturer´s recommended maximum pressure ($p_{max} = 0.8\ N/mm^2$). Room termperature was at 22 °C and curing time was set to 24 hours instead of 45 minutes. [12]

Same procedure was applied on CCLT boards. Here the top and bottom boards (1 or 2 layers) were prefabricated and bamboo rings applied afterwards. The Bamboo type Moso was purchased from CONBAM GmbH (Germany) with a length of 2.400 mm. As the column´s outer diameter, 40 and 80 mm were chosen. A manually operated crosscut pull saw FESTOOL – KS 88 E (Festool GmbH, Germany) was selected for cutting the rings with a height of about 13 and 23 mm. Due to insufficient clamping systems for the bamboo rods, the height varied between 11 and 13 mm and 21.3 and 24 mm.

The Bamboo rings were separately coated with glue and arranged on the prepared boards in a honeycomb pattern. It became obvious that the coating and assembly process are very time-consuming. Additionally, the amount of adhesive applied was rather unevenly distributed, which lead to an excessive consumption of glue. To achieve an equal pressing force on rings even of unequal height, a layer of sandbags was placed on the plate, and then the concrete slab was positioned on top. Therefore resulting pressing force could not be precisely quantified.

In order to arrange the top board evenly on the rings, it was necessary to mill the rings over. Preliminary tests using a thickness planer only resulted in the destruction of the rings. Since the available milling machine only has an usable work area of 600 x 500 mm, the panels had to be split down the middle first. The size was now 550 x 1100 mm. They were then milled in two stages with an intermediate step for re-clamping. By doing so, inaccuracies in the overlapping area of up to 1 mm occured.

After milling the rings were coated with glue as before and the second board was added, followed by the pressing step with concrete plate and sandbags on top.

After another 24 hours the CLT and CCLT boards were released and cut in a half to their final width b = 245 mm, ready for testing. Fig. 2 shows one sample of each cluster before testing.

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Figure 2. Test specimen CLT / CCLT with different bamboo diameter

4 – EXPERIMENTAL SETUP

The 4-point bending test of the panels was conducted in accordance with DIN EN 408 using a bending-testing-machine for steel-fiber reinforced concrete samples provided by TESTING Bluhm & Feuerherdt GmbH, at the Laboratory for Building Materials and Construction Chemistry at BHT.

The specimina were placed symmetrically in the bending test machine as shown in Fig. 4. The distance between a load point and the adjacent support is a = 300 mm. The load entry rollers are applied to the specimina with a preload of 1 kN. Following that step the vertical force (F) and the displacement were set to zero and the test was initiated. The vertical force was then set to cause a constant deformation of 5 mm/min until a strength failure occurred, defined by a 50% drop in load.

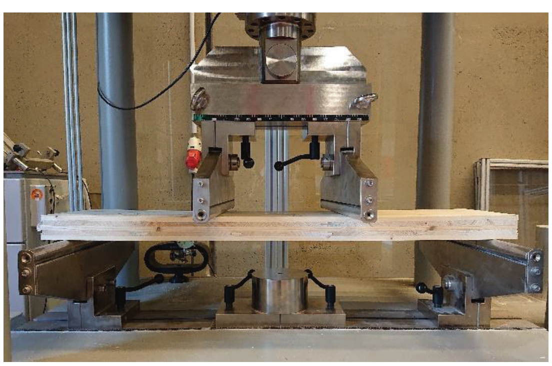

Figure 3. Testing machine with 5 layer CLT (scaled)

The single bending strength σ_m was calculated by equation (1), where *F* [N] is the vertical force, *a* the distance between one loading point and the adjacent support (here set to 300 mm), *b* the width of the specimen (here b = 245 mm) and the height *h* (50 mm).

$$\sigma_{\mathrm{m}} = \frac{3Fa}{bh^2} \qquad (1)$$

The mean value of every four results for each different combination was calculated, representing the averaged bending strength σ_{av}.

5 – RESULTS

Fig. 5 shows the results of this investigation. As can be seen, the bending strength of 5-layer CLT is the highest of the group with 31.2 N/mm² whereas a 3-layer CCLT arrangement with 40 mm bamboo rings reached only 14.55 N/mm².

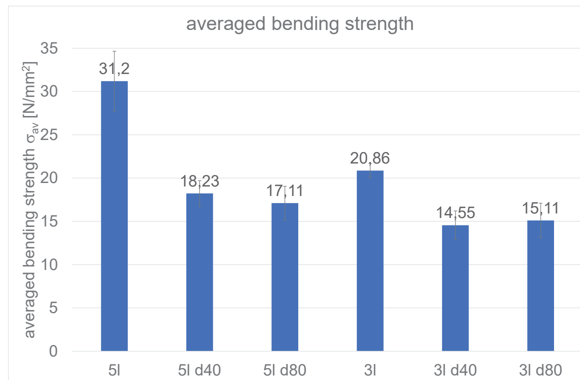

Figure 4. Averaged bending strength of CLT / CCLT at model scale [13]

The large difference between the scaled 3 and 5 layer CLT of about 30 percent (31.2 to 20.86 N/mm²) was unexpected.

The difference in flexural strength due to different ring sizes is not significant, at least for the two sizes considered. It is only around 6 percent (5 layers) and approx. 4 percent (3 layers). In addition, the smaller ring sizes of 40 mm achieved the better values for the 5-layer structure, whereas the 80 mm arrangement showed slightly better values for the 3-layer structure.

The standard deviation of the two types differs. While the CLT panels 5l have the greatest scatter with s = 3.45, the CLT panel 3l has the lowest scatter of s = 0.82. The comparison of the CCLT panels shows that for both types, the panels with a bamboo ring diameter of 40 mm have a lower scatter than the panels with a diameter of 80 mm. The deviation is around 24 % for the 5-layer panels and around 17 % for the 3-layer panels. [13]

When examining the standard deviation in conjunction with the damage pattern, it can be seen that a low scatter usually represents a similar fracture behaviour of the 4 individual samples. The strength values only scatter slightly, as all samples can only bear similar loads due to the same manufacturing conditions and therefore also envolved manufacturing errors (prefabricated as complete individual panels). This became particularly evident in the CLT panels made of 3-layers. All 4 samples failed at the same point and showed similar fractural behaviour, which can be attributed to the manufacturing process. Before the load test, a visible gap of the adhesive could be seen, caused by the curvature of the board lamellae. This indicates that the pressing force applied was chosen too low and that the time between planing and board production was too long. [13]

The partial detachment of the bamboo rings from the surface layers on one or both sides possibly indicates an uneven distribution of pressing force during gluing due to different ring heights. This emphasises the need to develop suitable sawing strategies and techniques that ensure rings of the same height and parallel cutting surfaces.

The following Fig. 6 shows examples of the different failure patterns observed during the tests and during the evaluation, ranging from failure of the cover layers (a) 1 - wood failure and 2 - rolling shear failure (b) shows failure type 3 - failure of the glue joint between the lamellae and in (c) failure of the bamboo ring joint. [13].

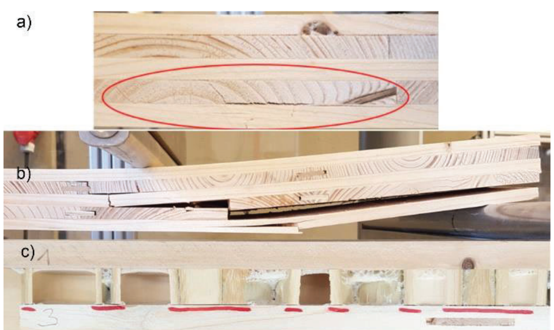

Figure 5. Failure of specimen [13]

The failing of CCLT panels only outside the zone of maximum bending moment could be due to the increased deformation on the bamboo rings in this area.Compared to bamboo, a massiv wooden core would be more flexible and could adapt better to the deformation. The bamboo rings, on the other hand, are very stiff and can only absorb a small amount of the deformation transferred by the wooden deck layers without separating from the wood. The resilience of the wood may therefore ensure greater flexural strength. This has already been observed in a similar way in earlier tests with glass fibre covered layers, where a whole series of rings sometimes shifted abruptly against each other. At the time, this was countered by roughening the rings´ surface and thus improving the connection via the cylindrical outer surfaces.

6 – CONCLUSION

In this paper the idea and the necessary conditions of substituting a large amount of timber in conventional CLT boards by using a bamboo core material has been demonstrated. As described, several problems occured while transferring the new COMBOO approach from a sandwich with FRP sheets of limited size to larger model scale CCLT. Especially the preparation and handling process have to be optimized, if the idea is to be used in civil engineering and architecture.

The development of a sufficient sawing process and suitable machinery including clamping and feeding systems is very important to create bamboo rings with parallel top and bottom sides and an ideally perpendicular outer shell. The applied milling step to homogenise the different height obviously takes too much time in large scale production. In addition, unevenly distributed and also insufficient pressing force leads to a low strength of the bonded joint.

Handling and gluing of the rings during assembling requires special attention and the development of suitable strategies, too. It was observed that the curing time of e. g. OTTO COLL was much shorter than the previous used for epoxy resins. Arranging the bamboo rings after adding the glue was laborious and the glue distribution uneven.

Further questions to be addressed could be the influence of ring density and ring size distribution on bending strength. It can be assumed that rings which were surrounded by other rings might be more stable as the glue will creep into the gap by capillary forces. This could reduce tilting under load and increase the glued contact area.

Cutouts for windows and doors in conventional CLT can be made easily by endmills or sawblades on CNC machines. The frames of windows can be connected by screws to the massive timber frame. In CCLT the middle layer is made of a honeycomb structure. So new strategies for inserts or other joining methods have to be developed.

Finally, further extensive analyses of an even larger test sample size are required.

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