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CCLT – Further development of a CLT based sandwich structure with a bamboo honeycomb (COMBOO)

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ABSTRACT: This document reports of extended investigations of a CLT sandwich construction. The required large amount of timber and the high weight of conventional CLT boards can be reduced by integration of a layer of bamboo rings forming a honeycomb structure (called COMBOO) between outer layers of CLT boards (=CCLT). After a transfer from GFRP sandwich applications via model scale tests, this document contains manufacturing and tests of full scale CCLT boards. First, a comparison between self-made CLT boards and CLT boards from manufacturer KLH (Austria) was made, to gather experience with handling and estimating the difference in bending strength due to much lower compression force during gluing. In the second step the CCLT boards were created which opened more new questions or tasks, followed by 4-point bending tests. Hereby was found that manufacturing method influences the bending strength, but the chosen manufacturing method can be used for CLT production and hence CCLT production. Bending strength varied between 30.6 N / mm^2 (KLH - CLT) and 8.9 N / mm^2 (CCLT). Additionally compressive strength of CLT and CCLT structure has been measured and a relatively similar value of about 3.6 N/mm^2 has been found. A wider field of new tasks and extend tests was identified to create a suitable building material at industrial scale.

KEYWORDS: CLT, honey comb sandwich, full scale tests, 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.

Timber has been used at all times as it was often widely accesible and can be machined with simple tools. It was a long journey from simple log houses to the "engineerd timber" of today, full of inventions and ideas. Whereas in the past 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 key factors in timber constructions.

Steel and concrete have their advantages which can't be neglected, but their need for energy during production is enormous. Another disadvantage nowadays is their CO_2 footprint, as large amouts of CO_2 are being generated or released during production. CO_2 is currently regarded as the main contributor to climate change.

Timber (like all plants), however requires and stores this CO_2 during its growth, which takes a while depending on species (about 70 years for spruce until harvesting). It is light weight, anisotropic and absorbs / releases water depending on environment which leads to shrinking / dwelling and sometimes deformation of simple beams or boards. Timber can be joined by different connecting means such as form-, force- and material-locking.

2 – BACKGROUND

The background section describes the base of this interesting research project and gives an overview of the conventionally used CLT material followed a description of a new CCLT approach and relevant basics according to it. Own work preceding the project is also presented.

2.1 CLT

In civil engineering and architecture, timber construction is becoming increasingly relevant, even for large-scale projects. The website "ctbuh.org/" lists the world's largest

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timber buildings completed by 2022, including buildings with heights of up to 85.4 metres (on 18 floors) in pure timber construction. [1] Fig. 1 shows the amount of high-rise timber buildings for the 6 countries with the largest amount worldwide, from a list of yet 15 countries, that realized pure timber and timber / concrete or steel buildings. The maximum height of all buildings and of the highest pure timber building were put on top of each bar. Norway's highest timber building for example is a pure timber building with 85.4 m. The earliest building is from 2009, a 29 m high residential building called "stadthaus" in London (UK). This can only be realized by innovative material combinations with advanced adhesive systems, that have been developed to enhance structural performance.

Drawing on the principles of glued laminated timber (glulam), which was first patented in 1906 by the carpenter Otto Hetzer, a panelized wood product similar to plywood was introduced much later. Since the early 1990s, this new material, known as Cross Laminated Timber (CLT), "Brettsperrholz" (BSP) in Germany or X-LAM, has been extensively studied and evaluated from the beginning [2]. The aforementioned buildings consist of Glulam and or / CLT materials.

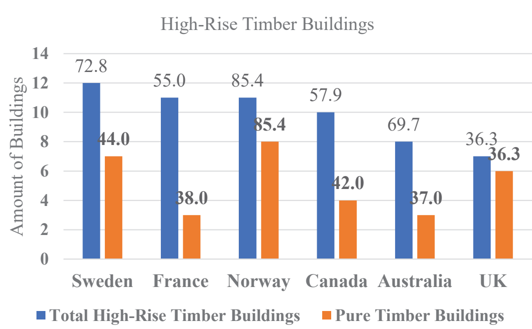

Figure 1. List of numbers of high-rise timber buildings (data from [1])

CLT consists of an odd number of layers of parallel-aligned timber boards, with each successive layer rotated by 90 degrees - similar to the structure of plywood. This crosswise arrangement significantly improves the dimensional stability of the panels. The individual layers typically range in thickness from 6 mm to 45 mm, while the complete CLT panels can reach thicknesses between 60 mm and 500 mm. [3] Their lengths extend up to 30 meters, and widths can reach 7 meters, though standard dimensions of approximately 3 × 13 meters are commonly used due to transportation constraints. CLT is primarily manufactured from high-quality northern woods, such as spruce and pine, with surface layers sometimes incorporating larch or Swiss stone pine. Experimental studies have also explored the use of hardwood species, including beech, birch, and tulipwood, as documented in the literature [4, 5].

The production process begins with the careful selection of raw timber boards, which are planed, finger-jointed, and arranged side by side. Typical adhesives from families like MUF, PUR and EPI were then applied between each layer mostly along the sides too, and subsequent layers are placed at alternating 90-degree angles. The assembly has to be compressed with high pressure using pneumatic or hydraulic presses, depending on the glueing system used. A schematic of CLT alignment is shown in Fig. 2.

Figure 2. Layer arrangement of CLT [6]

Although this process is predominantly carried out on an industrial scale by leading manufacturers primarily located in Central and Northern Europe, equipment for small-scale production is also available. A growth in CLT production is expected in the next years to a turnover of up to 3.537,9 million US-Dollars in 2032 from 1.024,4 million US-Dollars in 2023. [7] Next production steps include accurate formatting of the large boards on CNC machines (specific length / width, cut-outs for windows or doors), transportation to the construction site and assembly. The high precision in manufacturing tight high tolerances.

However, the production of CLT requires substantial quantities of high-quality timber. Therefore, alternative strategies to reduce or optimize material consumption or to enhance properties are of growing interest. Swiss company Lignatur AG (Waldstatt, Switzerland) produces large span boards so called "surface" or "box elements", where hollow chambers are integrated between a top and bottom timber layer. Another promising approach could be COMBOO, an innovative bamboo-based layer, that makes CLT a sandwich. [8]

2.2 COMBOO - a technical sandwich structure

Sandwich structures are an innovative and important material combination for various engineering applications,

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mainly in transportation (e.g. railways, ships or aircrafts) and construction (e.g. wind turbines, roofs). They usually combine good mechanical properties with low weight, superior to their source materials. They consist of two face sheets, separated by a core material, as can be seen in Fig. 3b.

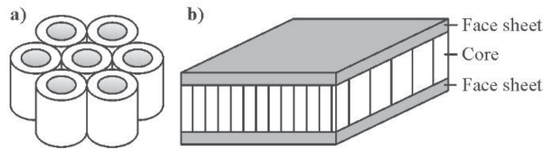

Figure 3. Ring structure COMBOO (a) and schematic sandwich (b)

The face sheets absorb tensile and compressive stresses, while the core absorbs shear stresses and distributes loads between the face sheets. Typical face sheet material were sheet metals, FRP (fibre reinforced polymers) or plywood depending on application, while polymer and metal foams, lightweight woods or honeycomb structures made of metals, paper and synthetic materials can be found as core materials. [5] Besides the structural needs, core and face materials and hence the sandwich can provide additional features like insulation or optical performances.

A problem especially of conventional core materials is their need for large quantities of energy during production (e.g. metal foams), oil for polymers or deforestation for monocultures in balsa wood production. An interesting approach especially for substituting the balsa wood could partly be palm wood, as it is a byproduct in palm oil production.

A more promising alternative for core materials is the use of bamboo, as it offers significant advantages. Bamboo is a fast-growing grass with heights of up to 40 meters. It offers high tensile (370 N/mm^2) and compression strength (> 90 N/mm^2) while storing CO_2 during growth. It is made up of cylindrical sections that are interrupted by so-called nodes [8, 9, 10, 11, 12]

Bamboo is a large family, native to all continents except Europe and Antarctica, although it can be found in Europe where smaller companies try to establish bamboo plantations e.g. in Portugal. Bamboo is comparatively undemanding with regard to the soil and can be used as a pioneer plant. [13]

The density of the fibrous structure varies over the diameter, the outer region is harder than the inner as opposed to to wood, where the core is the hardest part. The surface of a bamboo column is smooth even though it's very hard and repells colours or glues, so surface preparation can be necessary. The density of bamboo for technical applications is typically around 0.7 g/cm^3. [10, 12]

Beams and larger boards can be produced from bamboo too. Therefore stripes were created, planed or ground and glued together. Even bamboo veneers are available as these were sliced from pressed blocks. Companies like Moso International B.V. produce and sell these engineered bamboo products. Fire resistance can be problematic for load bearing applications. Charred stripes were reported to fall from the beams after the glue loses grip. This reveals new unburned surface and fire continues. [14]

The typical utilization factor of the source bamboo might be low as for several applications the bamboo has to be highly modified. Especially for common strip fabrication, a preliminary stage for several bamboo products, a large part of the bamboo is lost depending on diameter of the culm and wall thickness of the species in combination with the size of the desired stripes and number of stripes sliced from the ring.

A higher utilization factor can be reached when using bamboo rings. This approach was published first in 2016. It is called COMBOO, derived from honey**comb** and bam**boo,** which already represents a structure that can be used as core material. In the beginning it was combined with glass fibres and epoxy resin as face sheets to compare with sandwich structures with polymer foam and plywood cores. [8, 11]

Advantages of this core material, besides the low energy consumption during production are the referral on oil products and the better utilization factor. Bamboo beams or boards have a density of around 0.7 g/cm^2. The density of COMBOO is significantly lower with 0.2 - 0.25 g/cm^3, depending on the ring size, ring size distribution and ratio of inner and outer bamboo diameter. COMBOO structure is a combination of solid bamboo and air, that adds additional benefits like a good insulation factor as well. [8, 15, 16]

The bamboo culm has to be cut into rings of specific length, nodes have been removed at the moment. A previous equalizing step would allow to use these parts too and the reduce waste. Parallel faces of the bamboo rings are mandatory to obtain a constant glue line. Surface preparation by grinding, sanding, milling or sand blasting impoves the transfer of shearforces between the rings after gluing. Last steps were the arranging of the rings and the application of glue. [17]

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3 – PROJECT DESCRIPTION

As described in [18], a funding project as part of the "Lightweight Construction Initiative" of the Federal Ministry for Economic Affairs and Climate Protection of the Federal Republic of Germany has set itself the task of expanding the potential of sandwich structures for timber construction and thus reducing the high demand for high-quality timber in CLT. In addition to the potential savings in wood, there are advantages in terms of the weight of the CCLT structures, the heat transfer through the panels should be reduced and further functionalizations such as sound insulation or vibration damping could be realised.

Keeping the experiences of previous work in mind regarding handling and manufacturing of GFRP coated Comboo sandwiches or the model-scale CLT and CCLT boards, initial full-scale investigations were the next step in the project.

Therefore it was decided to compare first different specimen with a four point bending test. Comparison here was CLT (3- and 5-layer) from a professional manufacturer (KLH Massivholz GmbH, Austria) with self-created CLT (5 layer) and 5 layer CCLT with a Comboo middle layer, to gather further information about handling and manufacturing.

As the CLT from KLH had a height of 100 mm, the same height was chosen for the experimental approach. First step here was selecting timber. Pine wood boards with a size of 3500 mm x 150 mm x 27 mm had to be purchased from different DIY stores to meet requirements for CLT production. A single supplier didn't have the required amount of high quality material. Typical errors were strongly twisted material, too many or too big knotholes, large pitch pockets of tree resin or insufficient width. In industrial CLT production defective segments can be cut out and the remaining parts can be joined by finger jointing, which is not possible at this level of quality in a university's workshop. The boards were stored at 20°C and a humidity of about 55 % for a week before machining to reach similar conditions.

Moso bamboo rods with length of 2400 mm and an outer diameter of 80 mm were purchased from Conbam (Geilenkirchen, Germany). The first maching step was sawing the bamboo rings. Here a chopsaw (Kapex KS 80, Festool Germany) was used with a manual clamping system. This led to different ring qualities. The height differed between 21 and 23.5 mm. This sawing step is extremely laborious as the long rods are hard to handle. Over 350 rings had to be cut for the large CCLT-board. An (at least partly) automated system with suitable clamping is vital for any larger scale experiments.

The first step in timber preparation was planing the boards to a final thickness of 20 mm using a thickness planer. Then the boards were cut to a length of 2200 mm and 1000 mm (crosswise and lengthwise boards).

Then the first layer of pine boards was placed on a flat building surface. Here the professional CLT boards of KLH were used, as they provide a high surface quality. A separation sheet was put in between. It was found that boards were slightly twisted so it was decided to join only 2 layers by glue at a time and to fixate the first layer with screws in the underlying building surface. A single component polyurethane (PU) glue OTTOCOLL® P84 (Hermann Otto GmbH, Germany) was applied manually by 2 persons and then the second layer of pine boards (perpendicular fibre direction) was placed. A concrete slab with stacked sand sacks was put on top. The resulting pressure was only about 0.01 N/mm^2 which is only 1/60 th of the pressure required according to [19]. When checking the plates, gaps in the layers were found, probably due to the twisting of the boards and insufficient pressure. Major errors of about 1-1.7 mm were evened out with a hand planner, which worked out well.

The next production step differed for the self created or "own" CLT boards and the CCLT boards. For the own CLT boards, two sides were prepared as described before and then the middle layer of timber was added, followed by a pressing step.

For the CCLT boards, it was necessary to add the bamboo rings as a middle layer. First, the prepared rings had to be distributed on the board to make sure amount and pattern were correct. Each ring was then taken by hand and one side was covered with the PU glue and put on the board. Due to the large number of rings and the limited open time of the glue of 20 minutes [20], this step was done by two or three workers at a time. When all rings and half rings were placed in the core area, sand sacks were put on the layer. The surface was too uneven to place the concrete slab on top, so the pressure was once again reduced.

Before adding the second timber layer on the bamboo rings, the boards were put on a CNC milling machine to create an even surface. Here a industrial carpenters workshop (Tischlerei Streidt, Straußberg Germany) with an 5-Axis CNC milling machine supported the project and milled the large board. This step is unnecessary when prefabricating rings with similar height. Then the second timber board was put on top followed by adding the

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concrete slab and the sand sacks, after applying glue on each ring.

In order to increase the number of test samples, the CLT boards from KLH and the self created CCLT and CLT boards were divided in half using a handsaw (Festool TKS 75, Festool, Germany) and a reciprocating saw (Festool RSC 18 5,0 EB-Plus, Festool, Germany).

As second investigation, a compression test of CLT and CCLT had to be prepared. Bamboo has a very high compressive strength parallel to the fibre direction as described above. Timber, as aligned in this situation has a much lower compressive strength. The combined compressive strength is relevant for the manufacturing of CCLT boards and possibly also for its usage. On this account test specimen had to be prepared.

Keeping the high compression strength values of bamboo in mind, a specimen size of about 80 x 80 x 100 mm was selected at first. After the first tests yielded very low values, the specimen size for testing was increased to 200 x 200 x 100 mm. The manufacturing procedure was similar to the production of the large boards for four point bending tests. Boards with a size of 450 x 450 x 100 mm had to be prepared and separated afterwards for testing. Due to the much lower size, the test boards were milled at the BHT laboratory of production engineering on a smaller CNC milling machine (Datron MX3, Germany).

4 - EXPERIMENTAL SETUP

For good comparison between the CLT boards of KLH and the self produced CLT and CCLT boards, the same height was chosen, resulting in the same experimental setup for the four point bending test. The four point bending test according to DIN EN 408 is designed to estimate the bending strength of timber products in fibre direction. In the experiments the goal is to create a constant bending moment between the support, resulting in a shear-force free area with a pure bending load. Therefore the test specimen has to be put on two supports with a distance of about 1.800 mm (18 +/-3 x boards height). The total length of the test specimen has to be at least 19 times the board's height. Then the test stamp with two fins is moved against the test specimen with a constant speed of 0.3 mm/s. The failure of the test specimen has to be reached within 300 +/- 120 seconds.

After reaching the preset force the speed of 0.3 mm/s is set and the testing stamp with the fins is moved further until a load drop of about 30 percent of the previous maximum load occurs. While testing, the resulting force and the deformation were measured. Deformation measurement or value can be derived from the actual position of the pressure fins, as well as from three additional sensors that were placed on the lower side of the board. One sensor under each pressure fin and the third in the middle between the fins. This detail of the test setup is shown in Fig. 4.

To prevent large deformation of the timber in the support and pressure fin area, a sheet metal with a maximum height of 1/2 of the test specimen height can be placed in between.

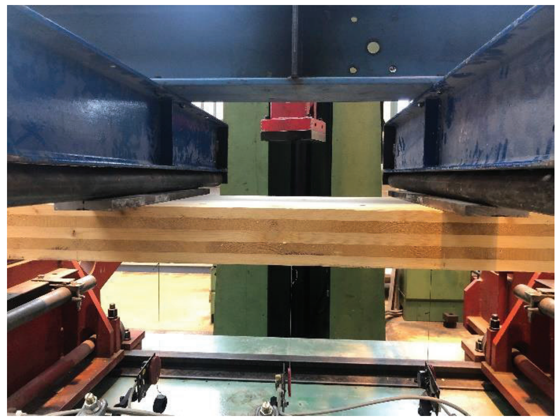

Figure 4. Pressure fins with sheet metal and deformation sensors

These tests took place at the department of civil engineering at the TU Berlin. The test machine was from the German company FORM + TEST Seidner & Co. GmbH (Riedlingen, Germany) with a maximum load of 140 kN per each of their up to 4 cylinders. It offers a maximum support distance of 10 meters and allows dynamic (only up to 4 x 120 kN) and static loads. The whole setup can be seen in Fig. 5.

Figure 5. Test setup at the TU Berlin with a CLT board on stage

The compression tests according to DIN EN 408 took place using a testing machine for steel fiber reinforced concrete specimens provided by TESTING Bluhm &

Feuerherdt GmbH at the Laboratory for Building Materials and Construction Chemistry at BHT.

5 – RESULTS

The four-point bending test revealed several results and a major difference between CLT and CCLT. First of all the comparison of average values between the 5 layer CLT from KLH and self-produced CLT showed a difference of about 24 percent higher values for the KLH material (33.45 N/mm²). The maximum bending strength of the KLH 5 layer material (40.6 N/mm²) was about 51 percent higher than average 5 layer self-produced CLT (26.8 N/mm²). The three layer KLH material reached an average bending strength of 30.8 N/mm². Finally the 5 layer CCLT reached 8.7 N/mm², which is about 27 percent of the average value of the 5 layer KLH CLT. Standard deviation was not calculated due to the low number of test specimens. The results are visualized in Fig. 6.

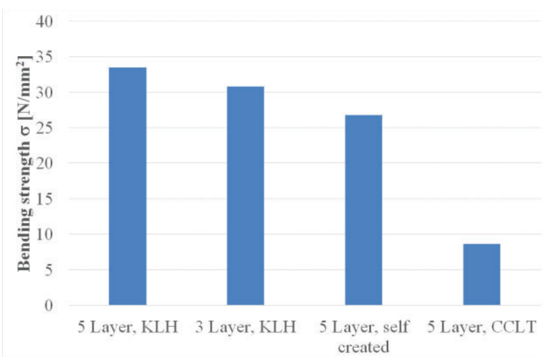

Figure 6. Comparison of bending strength

The results of the comparison of self-produced and industrial grade CLT are interesting to the extent that the relative results are quite similar, even though manufacturing was inadequate. The panels exhibited unevenness due to twisting in the lamella layers in combination with completely inadequate bonding (much too low pressure during bonding). The CCLT samples also had the problem of misalignment in the layers. This resulted in the additional problem of an uneven support surface in certain places for the rings, which had to stand on such structures.

As a result of this and the pressure applied using only sandbags when bonding the first side to the ring layer, uneven glue heights between the bamboo and the first surface layer resulted.

The results of compression tests are relatively similar for CLT and CCLT. For CCLT averaged values of 3.5 N/mm² (80 x 80 mm) and 3.4 N/mm² (200 x 200 mm) have been found with a standard deviation of s = 0.36, while CLT reached averaged values of 3.7 N/mm² (s = 0.24). [21]

The measured values are much lower than those of pure bamboo according to [22] and the CCLT cannot show better values as the weakest part, the pine timber, fails first. The failure of both materials is different. While timber shows cracks and compression of the whole structure, the CCLT specimen looked different. The bamboo rings acted as punch holes and punched deep into the soft wood. The next three figures show the specimens after testing. For better comparison an untested specimen was added in Fig 7 and 8.

Figure 7. CCLT n after testing in comparison to uncomressed [21]

Figure 8. Tested CLT specimen compressed / untested [21]

The effect of pressing in can be seen especially in Fig. 9, where the bamboo rings penetrated the upper layers of the timber. The inner area of the timber shows large cracks and deformation. A protective layer could be helpful for an even pressure distribution.

Figure 9. Large CCLT specimen after testing [21]

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6 – CONCLUSION

As already mentioned, other consequences not expected from [18, 23] became apparent during the production of the large panels. In addition to the significantly more difficult handling of the large surfaces when covering them with the bamboo rings in combination with a sufficiently fast adhesive application, there was also a challenge in generating sufficient pressing force. Larger irregularities due to twisted boards were provisionally evened out using a planer, but this is by no means a substitute for even pressing. In the future, a veneer spindle press will be available at the BHT for this purpose, which will provide sufficient pressing force.

The penetration of the bamboo rings into the surface layer material must also be quantified in further work, possibly in combination with the required pressing pressure during bonding. As the effective area in the bamboo layer is approximately 70 percent smaller than in the solid wood area, the influence of the pressing force is locally different. Any damage in the surface layers must be identified in order to achieve a compromise between the required pressing force in the wood-wood and wood-bamboo zone and the permissible deformation.

Ring production is also a major challenge. In the meantime, a corresponding sawing device with suitable clamping system has been developed that works partially manually. However, a fully automated system is being designed and built as part of the project in order to be able to provide the ring quantities and qualities required for the extended sample structures.

Other open questions such as required ring size, ring density or suitable connection systems were mentioned in [18]

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