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USAGE OF A BAMBOO HONEYCOMB STRUCTURE (COMBOO) IN TIMBER ARCHITECTURE

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ABSTRACT: This paper gives an overview of recent developments of the ecological bamboo based honeycomb like sandwich core material COMBOO and its usage in civil engineering and timber architecture. A brief introduction gives insight into to material bamboo itself and its excellent mechanical properties. The manufacturing process of the COMBOO structure will be described in detail. Previous results from mechanical validation, e.g. 3- and 4 point bending test as well as compression tests will be presented. Main focus of this paper is put on the interesting properties of the bamboo sandwich in acoustics and thermal insulation. The hollow structure with "entrapped" air provides here interesting properties. A good acoustical damping in a frequency range was observed with an artificial and a real COMBOO structure. The results were compared to common acoustic panels. The heat transfer comparison with conventional materials like concrete, double-glazed glass structures (windows) and aerated concrete reveals comparable or better insulation values. This makes the structure suitable for wall and floor elements, acoustic panels, transport boxes and structures in modern transport. Further improvements will be discussed.

KEYWORDS: COMBOO, core material, sandwich construction, insulation, acoustic panels, honeycomb

1 INTRODUCTION

Conventional core materials of sandwich structures mainly consist of polymer foams, metallic foams, aramid honeycomb or balsa wood. The materials are somehow environmental problematic as they consume large amounts of energy during production, were based on mineral oil or grow in monocultures.

A new approach called COMBOO uses honeyCOMB arrangement of bamBOO rings, where the face sheets were covered with glass or natural fibres and a resin. Another type of new material consists of top layers of wood or plywood and a core of bamboo rings, forming a sandwich.

Bamboo itself is a grass with a hollow stem divided by nodes and a hard outer rim. Big advantages lay in the CO_2 storage capabilities of the raw bamboo, the growth rate of up to one meter per day, the height of up to 40 m and its mechanical properties. A tensile strength of up to 370 N / mm^2 and a density between 0.6 and 0.75 g / cm^3 (for comparison: pine 0.45 g / cm^3) were reported. Density distribution across the stem is different to timber. The inner part has a lower density, increasing to the outer area. I can be harvested after just seven years and a reforestation is not necessary. [1]

Bamboo is known in Asia as building material for centuries, while it's nowadays often used for scaffolds, furniture, reinforcements for concrete walls, laminates, laminated beams or chopping boards, where the material is more or less processed.

Bamboo for beams, boards or laminate floor is usually cut in length into smaller stripes, than grinded or milled to receive a rectangular shape, arranged and finally glued together. The price for this procedure is losing the outer regions of the bamboo column with the highest density.

Machining of bamboo requires sharp tools, a coating on hard metals is recommended for milling and sawing. Holes perpendicular to length axis or screws / nails were problematic as the materials tends to split. Splitting of bamboo occurs often during drying. Penetrating the nodes might help. [1]

1.1 PROPERTIES OF COMBOO

Following the COMBOO approach and forming a sandwich structure, excessive machining or processing is not necessary. This saves lots of the overwhelming properties of the natural bamboo. Excellent bending properties, a good compressive strength and a delivery of light through the COMBOO structure if covered with transparent GFRP were interesting features of the new approach (e.g. lower right part of Figure 1).

In addition to the aforementioned properties, density of COMBOO structure through the arrangement of several rings is another main advantage. It is much lower than density of bamboo (wood) itself due to the proportion of wood and air. Density values of 0.2 and 0.25 g / cm^3 were measured.

Mechanical and geometrical properties depends on the chosen bamboo species and the diameter of bamboo, because this determines the ratio between air and material in the core layer. For example Tonkin-bamboo itself reached compression test values of 109 N/mm², while other species reach lower values e.g. Moso-bamboo 74 N/mm² (when using ring area for calculation). [2], [3], [4]

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1.2 IDEA OR APPROACH

The hollow chambers, filled with air, of the COMBOO structure can be used for another topic especially interesting for applications inside a house or factory, the soundproofing of walls.
Acoustic noise in our environment like household, office or at work affect human body. High energetic levels of noise of around 120 dB provide sudden pain and can cause Tinnitus, deafness or sudden hearing loss. But also much lower levels influence wellbeing or concentration especially in resting phase. Sleep disturbances, cardiovascular effects lower productivity at work or school and hearing impairment can occur as long- or short-term effects. [5], [6]
Energy and resource efficiency is a major aim of our time. A closed hollow structure from a natural and renewable source like bamboo could provide a good thermal insulation by the enclosed air. Nearly all bamboo species offer this hollow structure, which might also be also an interesting field of COMBOO usage.
Transferring and extending application opportunities of the new COMBOO structure from mainly mechanical engineering or transportation to civil engineering and architecture is scope of this paper.

2 MATERIALS AND METHODS

The manufacturing of the COMBOO structure itself consists of a few simple steps that can be done without a high level of machinery. For mass production or larger projects, another solution is required.
First, the outer surface of bamboo columns has to be roughened by using sandblasting or grinding. The second step is a cutting process of bamboo rings of equal height. The third step is the arranging of the bamboo rings in a honeycomb pattern in combination with a gluing (wood, plywood or sheet materials) or lamination step (natural or artificial fibres) on both sides, to form a sandwich material.
Surface preparations were found to be a good strategy to improve shear and bending strength of the sandwich, as raw bamboo has an adhesive or coating repellent surface. [2]
In Figure 1, the manufacturing process of COMBOO structure is shown.

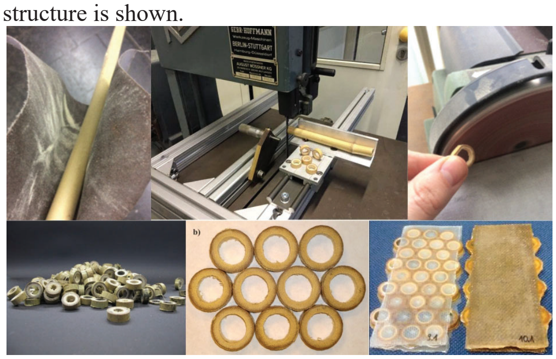

Figure 1: *Manufacturing of COMBOO material (grinding. cutting, deburring, arranging, laminating)*

Besides the flat board like structures, curved COMBOO components were possible too. The type of cover material artificial like fibres or renewable like wood depends on application. Therefore different strategies for connection have to be evaluated.

2.1 INVESTIGATION OF SOUND AND ACOUSTIC BEHAVIOUR

Sound is mainly understood as the spreading of pressure or density fluctuations in “elastic” materials like structures liquids and gases. It can be differed for our application into air-borne and structure-borne noise.
The Sound pressure level is the local pressure deviation from the surrounding or average pressure level. A higher sound pressure refers to a louder incident.
The frequency represents the number of pulsations of the sound per second. The sensitivity of human hearing is adopted to the frequency range of human voice of (250 - 2.000 Hz), but a range between 16 - 16.000 Hz or even higher can be recognized. [9] The range of frequencies interesting for room acoustics is between 100 Hz and 5.000 Hz.
Reverberation time is the period needed for fading of a sound incident to a specified grade. Allowable values depend on application (e.g. office, school or concert hall). It is influenced by sound absorption coefficient α, a value ranging from 0 (total reflection) to 1 (total absorption). Sound absorption coefficient α depends strongly on frequency. Measurement of the coefficient can be done by using an acoustic / reverberation chamber or an impedance / Kundt's tube. [10], [11], [12]
The impedance tube is often used for research and development due to its requirement of much smaller material specimen. It is limited to a sound incident perpendicular to the specimen, whereas a reverberation chamber can be used for a diffuse sound signal direction. In this work a Kundt's tube in single microphone arrangement was used, due to availability at university.

2.2 APPLICATION ACOUSTIC PANELS

The first approach presented here is the usage of the COMBOO structure as an acoustic panel used as absorber. Acoustic panels mounted to walls or ceilings were often used to improve the sound climate in offices, schools, concert halls or factories. A damping of the total amplitude or of certain frequencies or a reduction of the reverberation time can be the aim. Mainly used technical principles to achieve these targets were absorbers, plate transducers or resonators. They often work in a specific frequency range. [7]
Absorbers, often porous, transform the sonic energy into other energy forms mainly heat. Dissipation of energy is a result of friction or contact between air molecules with other air molecules and surrounding structures. Therefore, longer open and narrow pores are required. They often contain either mineral or organic materials. [8]. Porous absorbers can effectively be used for damping in the middle or higher frequency range

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Examples for "soft" porous absorbers were typical polymer materials in industry like rebounded foams mainly consisting of PU (polyurethane) and soft foam chopped recombined with a good sound absorption also due to its mass, melamine resin foam wits a low density but many pores, PU or viscoelastic foams. [13], [14]
Wood wool, textile fibre compounds, hemp fibres or moss were porous fibre based sound absorber. They were manufactured by adding cement and water, pressure and heat or a special conservation treatment to be formed. The often provide a wide frequency range for damping. [15], [16], [17]
Sandwich materials i.e. a combination of plates with mainly small holes, a carrier plate and often an acoustic fleece can be found in literature. [18]
Resonator systems were Helmholtz resonators, plate transducers or perforated plate transducers. The working principle is a spring mass design with an optimum working point at their resonance frequency. The mass is often timber, plasterboard or plywood or even air while the spring is an entrapped volume of air. Perforated plate transducers have a regular distributed pattern of holes or slots often combined with porous absorbers for a better absorption range. Common resonator systems can be mainly used at lower frequencies.

2.2.1 Manufacturing and preparation

One suitable way for acoustic measurement is using a Kundt's tube to measure the sound absorption and sound transmission coefficient of small samples with perpendicular sound incidence, as described above. Therefore several conventional materials for acoustic absorption or damping were prepared to compare with the COMBOO structure (ref. Figure 2).

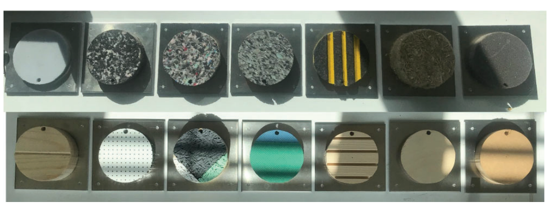

Figure 2: *Materials for acoustic comparison*

They were mainly cut out using a band saw, as can be seen in Figure 3, left side.

Figure 2*: Material preparation (cutting und gluing)*

Bamboo as a natural product is inhomogeneous. For homogeneity and better understanding of the effects, MDF (medium density fibre board) and wood boards with CNC milled holes (15 - 20 mm) were mainly used instead of the more irregular bamboo pattern. Bamboo rings were used for comparison.
The surface of the COMBOO specimen was covered with a 4 mm MDF layer with laser cut holes from 3 - 10 mm (ref. Figure 4). The hollow chamber under the top sheet can be seen as well.

Figure 3: *COMBOO acoustic panel [19] a) top layer b) core material c) bottom layer – left bamboo, right MDF based*

Plain or unmodified materials (aluminium, plywood, MDF, pine (slotted), pine) have been prepared for measurements in Kundt's tube too, to acquire comparable data of the unmodified surface.
Figure 5 shows prepared COMBOO style structures made of MDF, timber and bamboo.

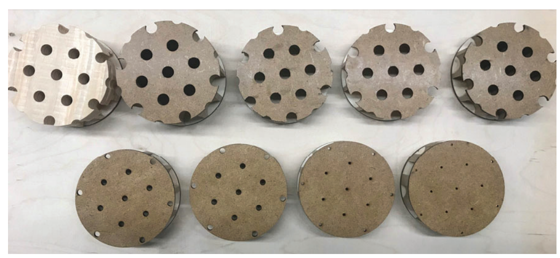

Figure 4*: COMBOO style MDF acoustic panels*

A MDF COMBOO specimen with a hole diameter of 20 mm (inner core region) and 10 mm hole (face sheet) was filled with polymer foam, to combine two absorber principles.
All specimens were mounted to an aluminium sheet, to be fixed at one end of the Kundt's tube. A speaker on the other side generates a signal at different frequencies, here in a range up to 1800 Hz, due to the tubes diameter. A microphone probe, guided through the test specimen acquired the signal, analyzed by an oscilloscope. The test setup is shown in Figure 6 and each test was performed three times.

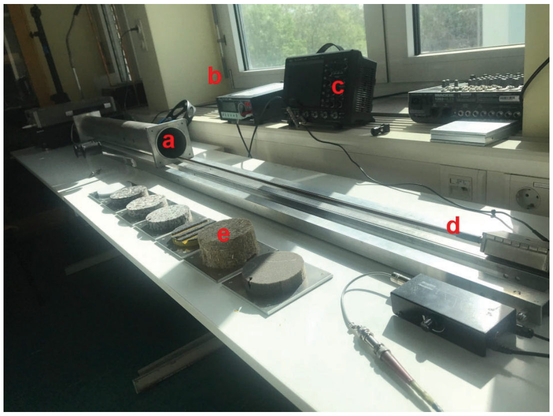

Figure 5: *Kundt's tube (a) and measurement setup (multimeter (b), oscilloscope (c), microphone probe (d), test specimen (e)*

2.3 INVESTIGATION OF THERMAL INSULATION / THERMAL TRANSFER BEHAVIOUR

Second approach is a comparison of heat transfer through different materials. Therefore five typical materials of civil engineering were chosen, set to identical geometric parameters including thickness. The specimen were the COMBOO structure with a 0.3 mm GFRP layer on both sides, concrete, aerated concrete, styrofoam and a double-glazed window with two 6 mm glass sheets (ref. Figure 7). The dimensions were set to 150 mm x 150 mm x 20 mm. A test chamber (1) according to Figure 7 was created, using a hot air gun (2) to deliver warm air at a temperature of 55 °C. Warm air goes in from left side (in) and leaves the heating area through a smaller hole on the right side (out) to prevent overpressure. Five thermocouples connected to a pc via a precision measurement device (4) (ALMEMO 2890-9- Ahlborn Inc. Germany) were integrated into the chamber to measure the temperature at different positions. The first thermocouple was placed in the heating zone, aside of the direct blast of the hot air pistol. Two thermocouples were located directly above a hole in a bamboo ring and over the covering ring surface (Figure 7, right) of the COMBOO specimen (3). Two thermocouples (T_1, T_2) are behind the rear wall of the test specimen. Additional thermocouples were placed outside for reference. A thermo camera (5) (Optris, Germany) in the front end of the chamber was used to acquire the temperature distribution over the whole surface of the specimen.

Figure 8 shows three different test materials in the heat box. Thermocouples can be seen on specimen surface

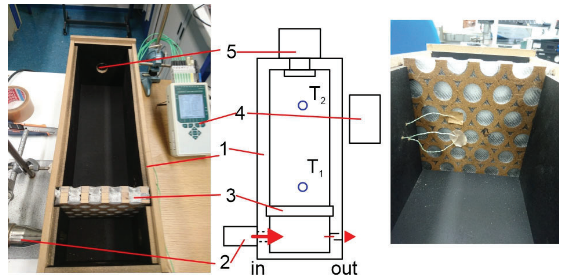

Figure 6: *Measurement setup and heat box (left / middle), thermocouples on "COMBOO" surface (right)*

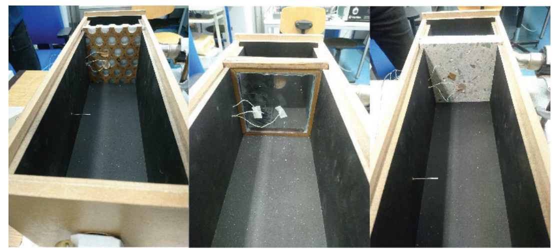

Figure 7: *Sample structures for thermal measurements*

The hot air gun was activated for at least 60 minutes after the initialization of the measurement devices. According measurement data have been logged. Between the investigations, the whole heat box was cooled down to ambient temperature.

3 RESULTS AND DISCUSSION

3.1 PROPERTIES FOR COMBOO AS MATERIAL FOR ACOUSTIC PANELS

First of all, the sound absorption coefficient was determined for plain or unmodified timber and metal materials. It can be seen (Figure 9) that all materials provide a damping of more than 40 % in the very low (f < 125 Hz) and respectively high frequency (f > 1250 / 1600 Hz) range. Even the aluminium sheet metal shows a damping of more than 20 percent starting at 1250 Hz.

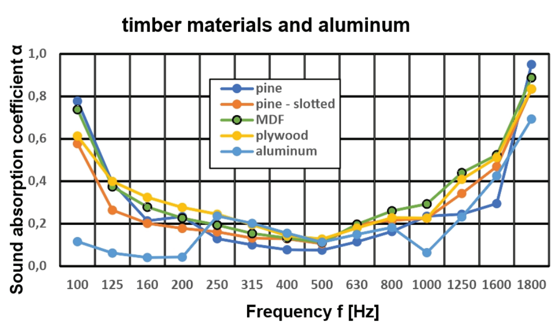

Figure 8: *Sound absorption coefficient α - unmodified materials*

Further experiments with soft wood like for example Balsa, Paulownia or the inner region of palm wood can be interesting here.

Absorber materials as presented in Figure 10 provide a better damping and hence a higher absorption coefficient.

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Especially hemp fibres reach values over 50 %, while wood fibres or wood sandwich material show values comparable to unmodified material. PU is also suitable for damping with a drop in the 500 Hz region.

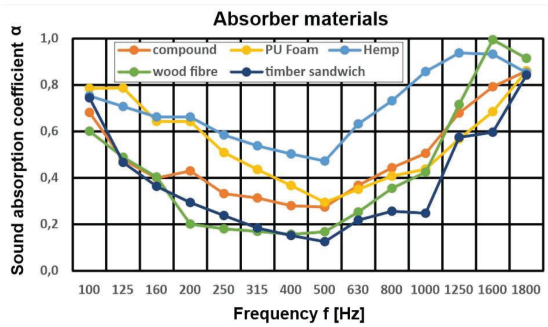

Figure 9: *Sound absorption coefficient α of absorber materials*

The acoustic composite foams reached these values in the range between 200 Hz and 500 Hz, while the absorption of the fibre materials depends on type of fibre. Special acoustic absorption sandwich materials show similar or slightly different values in a wider range, depending on structure and materials.

The sound absorption coefficient of the COMBOO structures reached α values between 0.2 and 0.56 in a frequency range between 315 Hz – 800 / 1250 Hz, as can be seen in Figure 11. It depends only slightly on inner diameter of the chamber (15 mm – not shown vs. 20 mm) but on the hole diameter of the cover plate. Best damping results have been reached with smallest borehole in the top sheet of 3 mm. Here is a peak at around 500 Hz, providing an extra damping effect. This can be found also at the lower hole diameter of 15 mm, but with slightly lower values.

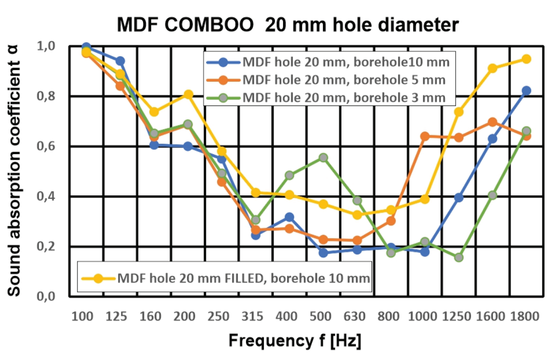

Figure 10: *Sound absorption coefficient α - MDF COMBOO – hole diameter 20 mm different borehole diameter in top sheet*

Very interesting are the results from combination of COMBOO structure with PU foam (yellow line in Figure 11), where a hole or chamber diameter of 20 mm with a borehole diameter of 10 mm was used. The curve is comparable to the unfilled structure but just shifted upwards by a factor to better absorption.

Hence a combination might be an alternative or an improvement to reach a wider absorption frequency range.

A difference between the artificial COMBOO structures (MDF) and real bamboo could not be found, so the MDF is a suitable substitute for experiments with directly comparable structures.

1.2 INSULATION / THERMAL TRANSFER PROPERTIES OF COMBOO

Several tests have been performed to identify material properties. The logged data were plotted over time and analysed.

A typical set of acquired data is plotted in the next Figure 12, here at the COMBOO structure with GFRP sheets. Immediately after starting the hot air pistol, the temperature increases in the heating zone. After approximately 2 minutes a temperature of above 50 °C is reached, after about 10 minutes the final temperature of 55 °C with light fluctuations.

The temperature directly on the surface of the test specimen is slightly different. Directly on a hole, temperature is 1 K higher then on massive COMBOO structure. The temperature increases from 26 °C to 36 °C and 35 °C respectively. Ambient temperature remains mainly constant at 31 °C but shows fluctuations probably from air movement in the laboratory. The temperature behind the test specimen remains quite constant. Both thermocouple positions (near specimen and in the rear part of the heat box) show finally a nearly similar temperature of 29 °C.

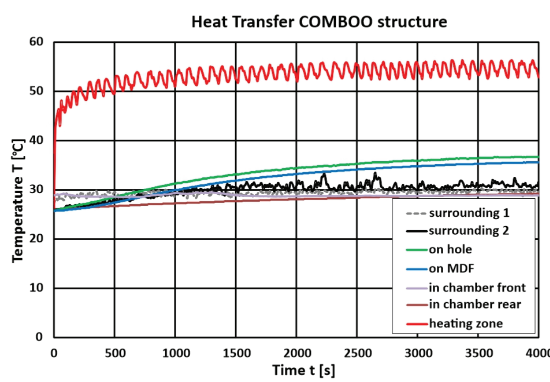

Figure 11: *Temperature data over time at different locations for testing COMBOO structure in heat box*

Next Figure 13 represents the measured data for all five test specimen. Two temperature values are given for each material. The blue column represents the difference in temperature between the heating zone of the test box at always 55 °C and the average temperature directly on the rear side of the test specimen. Green columns show the temperature difference between the average temperatures (T_1 and T_2) behind the test specimen.

Both columns of the Styrofoam represent the best results, as expected. The difference between heating zone and rear side of the specimen was calculated to 21.05 °C, while

difference between inside and outside of the test box is 2.55 °C.
COMBOO structure showed a lower surface temperature difference (18.85 °C) than the double glazed window (18.4 °C) and much lower value than conventional concrete (13.85 °C). The surface temperature difference of the aerated concrete was 20.5 °C and hence 10 percent better than the COMBOO structures value, which is attributed to the higher mass and the low conduction value, due to encapsulated air at small scale.

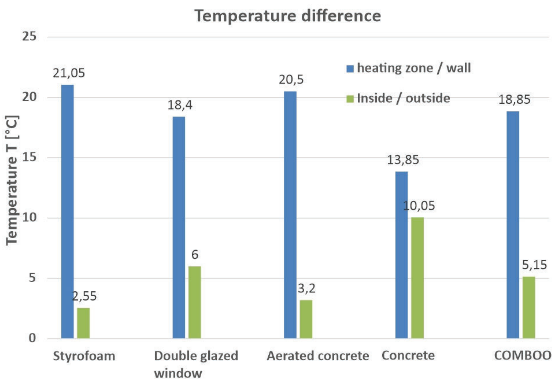

Figure 12: *Temperature difference between: heating zone and rear part of specimen (blue), inside / outside of test box (green)*

A multilayer or multi chamber approach within the COMBOO structure is currently under investigation, also in combination with plywood sheets as top and bottom material. It is assumed that relatively large volume leads to convection inside the chambers and hence a higher temperature exchange. Same problem would occur at the double glazed window with even higher total volume.
Especially the approach with plywood top and bottom sheet and a double layer COMBOO structure would provide a good insulation, a high mechanical stability and a conventional machining / manufacturing of floors and transport boxes.
The infrared camera was used to visualize temperature distribution over the surface area, as thermocouple represent only point measurements. The result is shown in Figure 14, where picture of the COMBOO structure are shown. Time steps are integrated into each single picture. It can be seen, that infrared radiation was detected by thermal camera. First of all temperature distribution is homogeneous in colour over the whole area, while with increasing time, colour of the holes turns to yellow. It can be seen, that temperature rises at the holes. Due to the camera itself, a temperature adaption takes place shifting the colour scale between hottest and coolest points.
In the upper left part of nearly all pictures, a small temperature leak can be seen, as insulation of the rim was disturbed. Camera measurements of the COMBOO structure couldn't be repeated, as a software problem of the old operating system occurred.
Temperature distribution for the other specimen was homogeneous over the whole area during each experiment. The glass surface had to be coated with black dye as reflection disturbed the measurements.

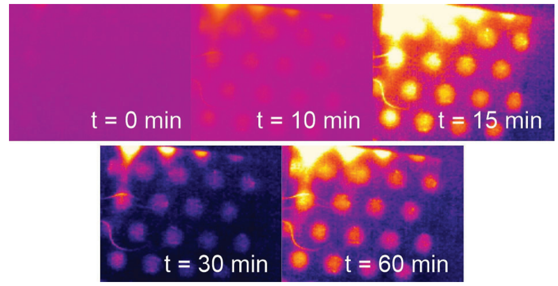

Figure 13: *Pictures of thermos camera at different time steps*

4 SUMMARY AND CONCLUSIONS

This paper described extended research for an alternative sandwich core material made of bamboo. The new material is called COMBOO and it provides not only superior mechanical properties like high compressive and bending strength but also good results in thermal insulation and acoustic damping.
The comparison of sound absorption coefficient in a Kundt's tube of composite foams, fibre materials and COMBOO structures revealed good damping or absorption results in a broad frequency range of the new structure. Different geometrical dependencies have been successfully identified, as the chamber diameter has much lower influence on damping value than the hole diameter in the top sheet. An enhancement of total absorption over the whole frequency range was received when filling the chambers with polymer foam.
Next steps will be an investigation of the effects of chambers depth, a combination of several different hole diameters at one top sheet material and different fillings of the chambers. This might improve damping, also over a wider frequency range.
A visible COMBOO structure (GFRP or polymer sheets) could be very interesting in acoustics if a sound absorption has to be combined with certain requirements of surface stability or stiffness. The specific honeycomb appearance could also be interesting. A fibre filling could provide interesting optical effects.
The other investigation in this paper concerned heat transfer or insulation characteristics of five typical materials for civil engineering. It was found that the heat transfer through a GFRP covered COMBOO board, acquired by the measurement of the surface temperature is lower than through double glazed windows or concrete panels of same thickness and slightly higher than through aerated concrete boards. Best insulation was reached by a styrofoam block.
Next research steps will be the estimation of heat transfer coefficients and improvements of the COMBOO structure. Therefore the thermal analysis of single GFRP sheets might help. The aforesaid multi-layer attempt could reduce possible convection and improve insulation.
In combination with the high compressive strength of the COMBOO structure, utilization as transport container conditioned box or floor material is possible especially if plywood is used as top and bottom sheet.

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5 OUTLOOK

In addition to the classic applications of the newly developed COMBOO sandwich material in the area of apartment, house and modular construction, its very interesting properties can also be used for technical applications such as acoustic insulation boards and thermal insulators. This also opens up applications in refrigerated box construction for trucks. A special advantage here is the recyclability of the material, which consists of renewable materials.

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