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CASE STUDY: DEVELOPMENT AND EVALUATION METHODS FOR BIO-BASED CONSTRUCTION REALIZED WITH PAPER-BASED BUILDING MATERIALS.

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Abstract

This paper presents a preliminary case study of a cladded skeletal structure built primarily with paper materials. The methods used regard construction detailing, finite element model analysis (FEM), material testing and ecological evaluation. The material behavior in relation with the application in construction is discussed. Existing studies are referenced to present a holistic view of the current status of the research. To explain how paper products can be used as construction materials, the pros and cons of the anisotropy of paper as a base material in combination with the manufacture processes used to form multi-layered components are addressed. The differences between current industrial and construction applications and testing methods are highlighted with the aim to target the steps required to create standardized processes for using paper products as construction materials. Within this context the current construction is analyzed and the assembly method, together with the custom made design of the multi-axial connections, is presented. The material testing includes compression tests performed with paper-tubes, honeycomb- and corrugated boards and a 4-point bending test performed only with paper-tubes. The material testing of boards is executed to examine their potential as load bearing elements and to evaluate the testing conditions. FEM analysis focuses on the skeletal structure whereas the wall panels are not considered as stiffening elements. The global structural analysis resulted in a diagram of principle stresses. The local FEM analysis is focused on the corner area where peak stresses occur. The comparison between calculations and material testing showed that the structural capacity of the paper-tubes is sufficient while the joints need to be reinforced. The ecological evaluation based on the method of life cycle assessment (LCA) indicates that the demonstrator fulfils the main requirements for circular design. All in all paper materials present great potential for application in construction.

Keywords:

Building with paper; bio-based building materials; paper materials; paper-tubes; boards

1 INTRODUCTION

At present the excessive consumption of natural resources and also the environmental pollution caused by building construction are matters that have gained great focus. A third of the waste produced annually in Europe comes from activities of construction or demolition and only 50 % of it is recycled [European commission 2017]. Hence alternative construction methods that are more sustainable have come to the foreground. Ergo, the more intensive use of eco-friendly renewable materials, that are also highly recyclable, is a strategy proposed with the aim to eliminate those problems. In these conditions the implementation of paper materials and their products in construction is the central topic discussed in this paper. As it is known, wood fibers are the basis material for all paper products that undergo through special forming processes in order to direct the fibers and create the desired layering of the material. Paper products are highly recyclable. They can be split into fibers and then reused to form new materials. Currently the "recycling rate of paper and paperboard consumption" in relation to the "utilization and net trade of paper for recycling" is approximately 72 % [Confederation of European Paper Industries 2017]. At the same time the recyclability of paper products improves constantly. Next to this fact, the evolution of paper materials has led to advanced technologies on the forming processes and simultaneously the development of components with physical and mechanical properties that create good prospects for application in construction.

There are some experimental studies and publications on this subject that present the strengths and weaknesses of paper materials for building applications.

To present a few examples, in the past two decades, TU Delft [Latka 2017], ETH Zurich [Pohl 2009], Bauhaus-Universität Weimar [Schütz 2017] developed research in this field. Distinguished architectural and engineering offices, such as those of Shigeru Ban Architects (JPN), Octatube (NL), ABT consulting engineers (NL), chose to experiment with the same materials and build temporary constructions [Octatube 2010]. Therefore, examples of construction details and results from selected structural tests are available. However, for many reasons, such as set of requirements of each construction project and variables within the production of the paper products implemented, it's not possible to generalize the findings, even though use for comparison is often helpful.

As it is known, the greatest challenges identified are related to the reaction of paper materials to fluctuation of temperature, humidity and the combined effects of those [Linvil 2014], as well as fire resistance. Due to the anisotropy and heterogeneity of paper materials, the effective distribution of stresses through the components is also crucial.

Consequently a more collective approach is needed in order to develop highly applicable methods for building with paper materials and overcome the aforementioned challenges. In this spirit, the background of this case study is the interdisciplinary project BAMP! - Building with paper- which aims to achieve the qualities and standards required for a lightweight, temporary, functional single storey house. Within the context of this project engineers from the fields of material science, chemistry, mechanical engineering, construction and design are occupied with all relevant investigations that are required in order to examine the physical and mechanical properties of paper materials, come up with solutions for improved performances, and experiment with the aspect of application in construction. This paper is a preliminary work that functions as an introduction to a few aspects of the research and a first iteration step towards the final goal.

The experimental case study presented, named as House 1 ('Fig. 1'), regards a full scale mockup of a skeletal structure built mostly with paper materials. The primary construction consists of paper tubes and the walls of honeycomb boards. The main aspects studied for the realization of it are the material behavior of the components made of paper, the structural analysis of the frame structure, the construction details with a focus on the joints and the assembly process. The aspects of humidity and fire resistance have not been encountered since more time is required to develop effective solutions that are also ecologically friendly.—The experience acquired from this practice-related study, the building process and development of testing delivered great benefits both for the different subjects that are presented hereby and the project.

2 METHODS AND MATERIALS

2.1 Material testing

In order to show the potential of paper as a building material and to perform some calculations, material tests were carried out. These tests are to be understood as preliminary tests for the development of standardized procedures for the further course of the project. As described in chapter 3.1 the focus of this paper lies on tubes, honeycomb and corrugated boards.

A common building material comparable to paper is wood. Accordingly, standards from both areas have been taken into account. The aim was to perform each test five times (evaluable measurements). The elongations reported were measured by crosshead travel. All samples were conditioned in standard atmosphere (23 °C, 50 % relative humidity (RH)) according to standard DIN EN 20187. This is a typical atmosphere for paper testing. Timber structures are often tested under 20 °C and 65 % RH [DIN EN 408:2012-10].

Tubes: The tested Tubes had an inner diameter of 100,5 ± 0,1 mm and a wall thickness of 9,37 ± 0,58 mm.

Axial compression tests were performed after comparison of two different standards:

- Testing of paper tubes: CT-107, Axial (End-to-End) Compression (July 2001).
- Testing of timber structures: DIN EN 408, compression strength in fiber direction.

For the same tubes also 4-point-bending test has been performed, in accordance with [DIN ISO 11093-7 2012].

Honeycomb board: Compression tests were carried out on an IDM MTC-500 test device. The Honeycomb boards had a corrugated structure in the middle and a thickness of 30 mm.

Honeycomb boards are used in furniture construction. According to [Poppensieker 2005] DIN 52376 can be used for compression tests parallel to the surface.

Compression test perpendicular to the surface (z-direction) was performed according to DIN 53291.

Corrugated Board: Compression tests were carried out on an IDM MTC-500 test device. A heavy-duty corrugated board with ACA fluting was used. Compression test parallel to the surface was performed according to DIN EN ISO 3037. This test is also known as ECT - edge crush test. The load direction is comparable to the compression test of the honeycomb board perpendicular to the surface. Comparing to the ECT standard additional 90° rotated specimens were tested (e.g. the load perpendicular to the corrugated medium).

Based on these material tests the demonstrator House 1 is developed as a load bearing skeleton structure.

2.2 Finite element method analysis

SOFISTIK software was used to perform global structural analysis in order to identify the loads acting on all parts of the construction and the peak stresses. In continuation ANSYS was used for local structural analysis, especially to predict local failure where the peak stresses occur. The exact conditions that apply for the simulations are described in paragraph 4.2.

2.3 Construction detailing

With respect to the characteristics of the paper materials in use common construction details were transformed to fit for the current purpose, focusing on the three crucial areas of fundament, eave and roof. The main criteria for the development of the construction method were easiness in assembly with use only of a few basic tools on site and the process of disassembly. A joining method to connect the paper tubes and form the skeletal structure was created as a result of experimentation with various solutions and prototypes. The joints were prefabricated. Computer aided design (CAD) was used to monitor the assembly process, predict possible problems and optimize the design of the joints [Cappelli 2007].

2.4 Ecological evaluation

The ecological evaluation of House 1 is based on the LCA method according to DIN EN ISO 14040, 2009 and DIN EN ISO 14044, 2018. The evaluation of the end of life within LCA is extended by the factor of deconstruction, hence detachability of connections and joints, to further evaluate the suitability of building components for reuse or recycling [Hildebrand 2017]. By this the circularity of the design can be evaluated.

3 PAPER AS A CONSTRUCTION MATERIAL

The first paper house documented was built by Elis F. Stenman in ca. 1922 in Massachusetts (USA). In the past 50 years the research on integration of paper materials in construction has been intensified for environmental reasons. The low cost of the material is an extra factor that makes it very attractive, especially for temporary installations for festivals, exhibitions or more importantly emergency shelters. A known example is the "Japan Pavilion", constructed in Hannover, DE (year 2000), a gridshell realized with paper tubes that are bent and connected with fabric tape [McQuaid 2003]. The architect Shigeru Ban developed various building systems for paper construction focusing mainly on the use of paper tubes and the structural typology of skeletal structures. A different structural typology that Ban developed is a stacking system suitable for load bearing walls meant to support a single storey house [McQuaid 2003]. At the same time, frequently, he combined paper materials with common construction materials either for areas with demanding structural requirements (such as joints, foundation, building skin) or for transparency [McQuaid 2003].

Some existing works in the field of research have been very helpful references as a basis for the current work. For example the overview of possible applications of "paper in architecture" developed by Jerzy Latka that focuses on temporary homes and instant shelters [Latka 2013]. To a different extent, the studies of Julia Schönwälder on the mechanical behavior of paper materials and customized beams made of a combination of paper materials have been very enlightening [Schönwälder 2007].

3.1 Mechanical behavior of paper and paper products, as a result of the manufacturing processes

There are about 3000 kinds of papers with different qualities produced for a great variety of applications [VDP 2015]. In general, the bearable loads of paper differ in machine and cross-direction due to the production process. The machine direction (MD) usually has higher tensile stiffness than the cross direction (CD) and also the elongation values differ [Niskanen 1998]. As paper is very thin, it performs much better in applications where the paper is under tensile load than in applications where it is under compression load. The strength of paper under compression is only about 30 % of the strength under tensile load [Niskanen 1998].

Corrugated boards, tubes and honeycomb boards are products of paper converting processes. Corrugated boards and honeycomb boards are usually used under compression so that the load is introduced perpendicular to the corrugation. In everyday life it can be seen in shipping cartons, which have to be stackable, without being crushed [Blechschmidt 2013]. Tubes are often used in winding processes (e.g. paper machines, textiles, yarns), so the important properties are concentricity and in connection therewith bending stiffness. Another point is the clamping of the tubes. Axial compression is less important in these applications than, for example, radial compressive strength. The manufacturing process also plays a role, as the products are available in various designs: Tubes are wound spirally or parallel [Blechschmidt 2013], honeycomb boards are available with a honeycomb structure or a corrugated structure in the middle [Poppensieker 2005]. The honeycomb boards referred to in this work have a corrugated structure. The base paper also plays a major role in the production process and influences the properties of the semi-finished products. Basically, a distinction can be made between virgin fiber material and recycled material. The most commonly used tubes are spirally wound tubes made of recycled material. In summary, all semi-finished products, as well as the papers themselves, have a preferred direction for the load application. In construction applications, it is very important to consider the strengths and weaknesses of the material in each load direction.

A problem is that paper standards are made for applications like packaging and not for construction. Loads are applied faster than for construction materials as shown in the comparison of CT107 and DIN EN 408 in chapter 4.1. Another point that becomes clear from the comparison is that the scales in building applications and also for the testing of components are much bigger than they usually are for paper and the semi-finished products. The failure criteria change when testing a 100 mm sample of a tube or a tube with the dimensions of a column (in the order of meters).

FEM analysis, especially for common construction materials like steel, is highly applicable in structural engineering. At the moment there are no material models for paper that represent the behaviour extensively enough to carry out simulations comparable to those for steel.

Facing all the challenges some restrictions and simplifications had to be made for House 1. The project aims to develop new materials and methods but in this first iteration step, only standard market available products were considered. The variety of available products has been further reduced to tubes, honeycomb and corrugated boards. As the time frame for the construction of House 1 was only about two months, the fast availability of the materials was a further criterion.

3.2 Construction outlines

House 1 covers a surface of 10 m^2. It was constructed on April of 2016 and remained erected approximately for a year before dismantling. It was built inside, to avoid combined effects of alternating climate conditions, the effects of creep and overall all the unstable parameters of a dynamic environment. The overall dimensions of the structure are 3 m · 3 m · 3.75 m. The building method is based on the use of paper tubes as columns and beams connected with multiaxial joints to assemble a frame structure. Similar examples of construction have been examined for emergency housing [McQuaid 2003].

The vertical section of the house is stiffened throughout the triangle formed at the area of the roof and the ground fixations. Since the structural tests indicated that the tubes present great performance under axial compression the integration of tensile ropes, mounted on the joints, was considered as a way to stiffen the construction. The ropes would be spanned within the boundaries of the blind facades and also the horizontal plane on the level of the eave.

The construction details, as presented in ‘Fig. 2’, were developed to avoid cold bridges and seal the open seams to protect the building elements.

The joining method is based on form-locking, mainly for the creation of the multi-axial geometry and force-closure generated by friction, for the fixation of the multi-axial joint in the tubes. The joints are plugged in the tubes from the side. Four different types of joints were designed for this structure. The design of each type was affected by the structural requirements and the desired sequence for the assembly. The joints used to mount the structure on the foundation follow the same principle of form-locking.

The assembly of the primary construction was planned in three main steps. First all joining elements designed for the XZ plane (‘Fig. 1’) of the multi-axial nodes were inserted in the tubes, so that the three main sections were assembled individually. Then the intermediate beams, along XY plane were added on the side sections (with an angle of 90 °). Finally the three construction parts were fixed together at the joints of the middle section.

The composition of the walls was planned as following: a multi-layered component made of 10 layers of 30 mm thick honeycomb boards, 5 layers of 4 mm thick paperboard on the outer side and a 5 mm layer of paperboard on the inside laminated together (‘Fig. 2’). The final wall element has a total thickness of 305mm and an estimated U value 0.235 W / (m² · K) [Bach 2016]. Based on draft calculations the wall panels can function as loadbearing elements. The walls were fixed on the main construction with steel threads bolted on the outer side. As shown in ‘Fig. 1’, for the mock-up, the cladding was assembled only out of a single layer of honeycomb board for reasons of economy in the material.

All elements were prefabricated. The joints were made of medium density fiberboard (MDF), manufactured with laser-cutting process. All other elements were cut in advance in the required dimensions. The assembly process was managed effectively only with the use of a few hammers and two ladders. All connections are reversible.

Fig. 1: House 1, the full scale mockup.

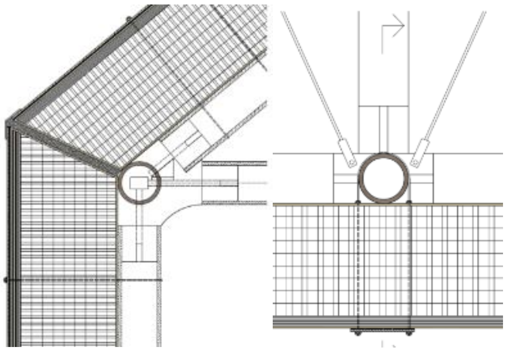

Fig. 2: Construction details, horizontal and vertical sections.

4 EXECUTION AND RESULTS OF TESTS

4.1 Structural tests of construction elements

The following subchapter presents the testing process results and some observations.

Tubes: The testing machine is not located in the standard climate. The samples were stored in plastic bags and tested under 22 °C and 29,1 % RH.

CT-107 specifies a specimen length of 100 mm and a crosshead speed of 13.3 mm/min. Compared to that DIN EN 408 specifies a length of six times the cross section and a force maximum within 300 ± 120 s. As the test was planned from a papermaker’s point of view, the testing device and the amount of test material were limited, a specimen length of 100 mm was chosen. Plane-parallel faces are decisive in compression testing. To ensure this, the end faces were machined in a lathe. After the first test the crosshead speed was stepwise reduced to 2 mm/min to approximate a static load as suggested in the DIN EN 408. The force maximum occurred within 67 ± 3 s. The mean maximum axial compression force occurred at 31,045 ± 2,228 N after a mean compression of 2.22 ± 0.1 mm. An interesting observation was made during all axial compression tests: The tubes started twisting. This effect is also reported in literature [Beatty 1980] and can be explained by the spirally winding process. A superposed twisting in a bearing, for example a node, means an additional load on the node. Further tests with tubes from parallel winding processes have to be made, specimen length and test speed have to be discussed. Further investigations could show the influence of the winding process itself and the influence of fiber orientation in the tube. For more precise evaluation of the elastic part in further tests optical measurement of the strain can exclude influences by the machine. The same statement applies to the tests of the other materials.

Regarding the 4-point-bending test, the dimensions can be taken from ‘Fig 3’. The testing speed was 10 mm/min. The supports have the shape of prisms based on DIN ISO 11093-6 2005. The main advantage of the prisms is the prevention of ovalization of the cross section while bending.

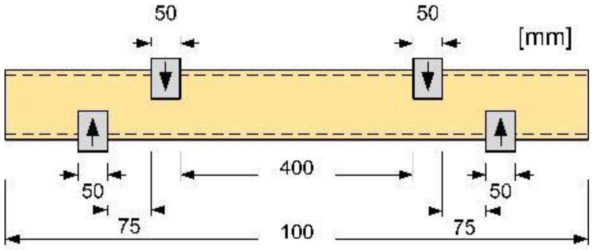

Fig. 3: Setting of the 4-point-bending test.

The tests have been performed by a testing machine Zwick Z050 with a 50 kN load cell.

The results for 6 specimens show that the force with which the tubes begin to break at 9.766 ± 0.329 kN. This equals to a moment at about 1.221 kNm and a lateral force at 4.883 kN in the tube with dimensions as marked in ‘Fig. 3’.

The same kind of 4-point-bending test was executed for a linear joint between two tubes. The comparison of the results with those of the previous test shows that the linear form-locking wooden joint has 80 % of the strength of a tube under bending.

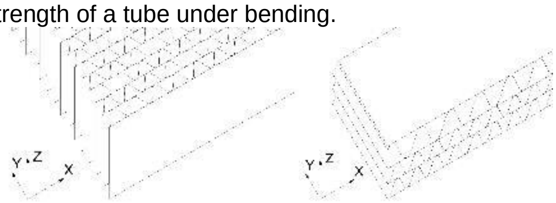

Fig. 4: Honeycomb (left) and corrugated (right) boards.

Honeycomb board: The mean maximum compression force in z-direction is 2,001 ± 89 N. If this value is related to the cross-sectional area, the expectation is confirmed that the highest breaking force occurs in the z-direction in comparison to the x- and y-directions. The test speed was set to 0.9 mm/min what is 0.03 · h_0/min, where h_0 is the thickness of the plate. The samples had a size of 50 mm · 50 mm. The different test speeds and specimen geometries make a direct comparison difficult.

According to the standard, the specimens were cut to a width of 50 mm and a length of 120 mm for tests parallel to the surface. The maximum force should be reached within 90 ± 30 s. The test speed was set in x-direction at 2 mm/min and in y-direction at 2.7 mm/min. Measurements in all three directions are necessary for a material modelling.

The values for the compression test in x- and y-direction (parallel to the surface) can only be used as a thumb value. A larger sample quantity is required for more precise statements. On one hand the variations come from specimen preparation. E.g. it is difficult to achieve clean, smooth cuts with standard workshop equipment. The importance of precise sample preparation is known from the field of corrugated board testing [VDW 2018]. On the other hand especially in y-direction it's more of a structural failure than a material failure. It has to be discussed if the force maximum is a reliable value because the failure is initiated much earlier and the area of plastic deformation should not be reached in building applications. The maximum is announced by a crumpling of the liner and it can be expected that the outer liners carry most of the load. In x-direction the force maxima was higher than in y-direction. This was expected because the inner liners support the structure by carrying the loads. In general the specimen geometries and testing procedures have to be revised for the project. The tests parallel to the surface were also performed with the loading in the direction of the 50 mm long edge instead of the 120 mm long edge. This leads to a geometry that is more comparable to ECT (corrugated board). An advantage is that more of the core elements are loaded and this leads to a better averaging. The tensions were in a comparable order of magnitude but some inconsistencies occurred evaluating the elastic behaviour for both loading directions.

Corrugated Board: The mean maximum force from ECT was determined to be 2243 ± 129 N. Related to the cross-sectional area this value is higher than those for the honeycomb boards. In the case of heavy-duty corrugated board, liners with a higher grammage are used than the middle liners of the honeycomb boards. As already mentioned, the liners carry a large part of the applied load. In terms of construction, one advantage of corrugated board, which is used as packaging material for cartons, compared with honeycomb boards, which are designed for surface loads, is evident here.

The loading of a corrugated board turned 90 ° to the ECT is an atypical load case. The mean maximum force was found to be 1324 ± 111 N. Similar to the testing of honeycomb boards in y-direction there is no distinct maximum, because the corrugated medium pushes together like a spring. The force therefore remains on a plateau after reaching the maximum and does not drop as much as in the other direction of loading.

As corrugated boards were not included in the realized demonstrator no further investigations have been made but are planned.

4.2 FEM Analysis

To execute the numerical structural performance investigations for the skeletal structure and the joints two main steps were regarded. An external horizontal static load of 1 kN (the weight of a person leaning on the structure) was set to one of the corner joints, at the height of the eave (‘Fig. 5’).

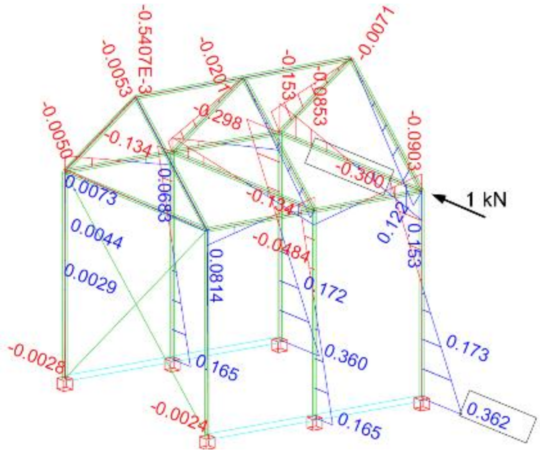

Fig. 5: Horizontal load of 1 kN and resulting bending moment m_y in [kNm].

First the global structure was observed. In order to perform the simulations House 1 was transferred to a finite element model composed of beams while all connection points were assumed to function as rigid connections. Using a sufficiently defined material model for the paper tubes the resulting stresses and deformations were approximated. Besides the cross section of the tubes a simple material model was assigned (isotropic elastic with Young’s modulus E = 728 MPa and Poisson’s ratio v = 0.2). The Young’s modulus is a result of the axial compression test, while the decision for the Poisson's ratio was based on the testing results reported for the project "Library of a Poet" [McQuaid 2003]. The stiffening diagonals were assumed to be steel cables with a higher stiffness comparing to this of the tubes. This way the distribution of stresses in the system and the resulting internal forces and moments were determined. The result of that simulation could be used to examine further any structural node of the system.

In the next step the internal forces were implemented on a small part of the structure, a detailed model of a corner joint that was found to be the area with the highest concentration of stresses. The results of the bending and torsion moments and normal and lateral forces acting on the node, where the highest values occurred, were transferred to a volume element model (see 'Fig. 6'). These loads are transferred to the node through the contact surfaces with the tubes. In order to decrease the time needed for the execution of the simulation, the tubes were excluded from the model. The relations between the separate parts of the joint were integrated in the FEM model and the mechanical properties of MDF were given as an input. The MDF material of the joint was modeled as isotropic elastic with a Young's modulus of $E = 5500$ MPa [Homanit 2003] and an assumed Poisson's ratio of $v = 0.3$ [Wood based material 2018]. For contact areas between two plate parts of the node frictional contact with a sliding friction value of 0.4 [VDI 2700 Blatt 9 2006] was assumed, except for the cases of multi-layered parts. At these contact areas where two parallel plates were screwed and pressed together, bonded contact was assigned. A geometrically nonlinear large deformation analysis was executed.

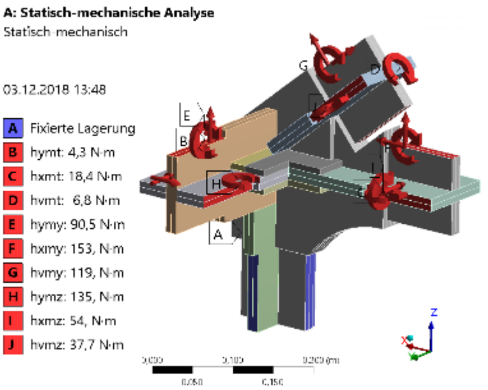

Fig. 6: Boundary conditions: loads (red) and support (blue) applied for local FEM analysis.

The calculation results showed a maximum displacement of 4.2 mm at the end of the node's y-direction. For statements about material failure the principal stresses were considered. The maximum stress value is about 86.7 MPa while the equivalent principal strain value is 2.06 %. The results for the principal stresses exceed the maximum stress value of 45 MPa [Homanit 2003] as resistance. So we can assume that the material gets damaged with the acting load of 1 kN. The maximum force which the structural system is capable of carrying can be determined by linear interpolation. This leads to a load capacity of 0.6 kN.

4.3 Ecological Evaluation

In order to obtain a holistic overview of the ecological performance of a construction, it is of central importance to consider its entire life cycle.

According to DIN EN 15804, 2014, the life cycle of a component is divided into 17 life cycle phases. In general, a distinction is made between production phases, use phases, deconstruction phases and the recycling phase. The usage phase is left out in this evaluation.

In the manufacturing process, the majority of the materials used have a low ecological footprint, as the corrugated sheets and sleeves are based on the renewable raw material wood on the one hand and are manufactured from recycled fibers on the other. According to [Cripps 2004] and [Cekon 2017] paper materials have a very low ecological impact compared to other building materials.

In addition to considering the used materials the joints and level of connectivity, hence the time and energy required for erection and dismantling of a construction must also be evaluated. Due to high degree of prefabrication of all construction elements the assembly of the skeletal structure and the walls, as described in 3.2, can be realized within short time.

The joints are destructively detachable but separated to pure material which is fraction B according to [Hildebrand 2017]. Accordingly, the materials used can be further recycled, thus close the material cycle.

5 CONCLUSIONS

5.1 Structural analysis – material testing and FEM

At the moment there are no standards for the testing of paper construction components. Unlike steel, there are still no material models that can be used to predict the material behavior of paper. Part of the project is to collect the necessary data for material modelling, to validate the models and then to use them for static calculations and assembly design. In order to advance the development of material models and assemblies in parallel, an approach called "application-related testing of semi-finished products" was developed in this first iteration step. Semi-finished products in this case are e.g. corrugated boards, honeycomb boards and paper-tubes. The approach consists of six steps:

1. List the components of the demonstrators.
2. Categorize the components.
3. Identify local and global failure.
4. List standards and test procedures.
5. Measure relevant imperfections.
6. Test material, revise procedure.

A distinction between local and global failure is necessary. The short specimens of the tubes showed a twisting. In contrast, buckling can be expected if the entire length of the tubes in the demonstrator is considered. The same applies to walls made out of honeycomb or corrugated board.

The standards taken into account under point 4 are standards from the fields of paper and board testing and structural timber. The conditions for this test have to be adapted to determine values that are needed in construction. Especially the dimensions shown in 'Fig. 3' have to be adjusted, so that a failure only on bending can also be analyzed. This requires further research on the tube's load and stress state during testing.

Imperfections are deviations from the ideal state. E.g. buckling is more probable to occur if there is already a curvature before the load is applied. There are already some measurements that are standard, e.g. roundness deviation of tubes, but others need to be developed or adopted from other areas of application.

In the further course, more attention must be paid to the elastic region of material testing, since the maximum bearable load must not be reached in the construction application. Precise, e.g. optical measurement of the elongations is necessary.

Currently it is difficult to obtain the necessary material parameters by research. For this reason, a material database is being set up, that compiles the corresponding values for selected materials. In addition, some materials are characterized in such a way that a simulation of the material itself but also of components is possible. Some challenges regarding material testing still have to be solved. One of the major challenges, for example, is the determination of the shear modulus.

5.2 Construction

A comparison between the diagram of stresses from the global structural analysis and the results of material testing of paper-tubes both for axial compression and bending indicated that the beams and columns can sufficiently carry the load of 1 kN as defined in ‘Fig. 5’. However, as stated in the end of 4.2 the joints need to be strengthened. There are various aspects that could create a positive effect and increase the structural capacity of the joints, such as higher material thickness or a stronger fiberboard. Due to collision between the edges of the joints and the inner surface of the tubes in case the material thickness would be increased further treatment of the plates, to smoothen the edges, would be required. Another option is to improve the connection between the tubes and the joint by adjusting the design. In this case, a solution is to add material between the crosses – interlocked plates- to distribute the forces more effectively. A change in the manufacturing process could also help. The use of CNC milling instead of laser-cutting would allow for use of thicker material. Then the integration of mechanical fixations between the joints and the tubes would also be possible. This way a higher degree of security can be reached.

Regarding the assembly method, due to the small size of the demonstrator the assembly was planned to start from preparing the two identical sides of the house and finish in the middle section. This method could be improved to allow for assembly of multiple sections in a row.

The assembly method of the external walls could also be improved. At first, even though the flat pressure profile allows for fast assembly (see ‘Fig. 2’), it has the disadvantage that the steel threads penetrating the panel are fixed on the outer surface. If the house would need to perform in real conditions problems with condensation could appear, damage the panels and at the same time decrease the effectiveness of the joints. Therefore, these fixations shall be hidden. Secondly, the contact surface between the round columns and the flat wall panels could be increased. To do this, either the shape of the wall-panels, at the areas of the inside corners, would need to be adjusted, or extra elements (longitudinal spacer profiles) could be integrated to absorb movements. In this case the impact on the manufacturing process required to form and finish the panels shall be considered.

Furthermore, to block heat transfer and improve the thermal performance of the wall, using thin layers of corrugated board rather than honeycomb board would be a great option. Corrugated paper is more than 100 % recyclable [VDW 2018] and Germany is the No. 1 supplier in Europe.

5.3 Ecological analysis

The developed case study fulfils the main requirements for circular designs through the selection of renewable and already recycled raw materials and the application of joining principles that allow the disassembly of the used materials by pure material. By replacing the MDF parts and using corrugated cardboard instead of honeycomb, the ecological footprint could be further improved.

6 OUTLOOK

As a general observation, in the next steps the results from material testing shall be used to develop constructions that work in favour of the strengths of paper materials. Within this spirit there are several ideas also on how to replace for example the MDF material used in the current case study with paper products. To achieve this more assembly methods are being investigated.

To develop reliable FEM analysis, a material library, based on the testing results, shall be developed. For this reason the application related testing (points 4, 5 in 5.1) shall be further developed. Gradually, a safety factor for the different paper materials could be defined.

Overall, based on existing research, paper materials present great potential for application in construction. Within the context of Project “BAMP!” more experimental structures that will also correspond to real conditions will be developed and tested.

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