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DESIGN AND NATURAL MATERIALS – INNOVATIVE APPROACHES FOR A SUSTAINABLE FUTURE ARCHITECTURE AND STRUCTURAL ENGINEERING

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Abstract

Perceptible limitations of resources, energy and agglomerations of waste cause modern societies to consider and expand research on sustainable and natural principles. In this context, the building construction sector, with its large impact on material consumption and landfilling, requires special attention and consideration. Strategies may include: using recyclable materials, reducing material waste and entropy, and using bio-based materials that can be returned to the natural material cycle without any treatment or separation processes.

The paper gives an insight into the design and elaboration of lightweight metal sheet structures, approaches to the use of raw wood for structures and structural purposes, and the material design of mycelium composite components for construction purposes. Parametric design tools enable the control of complex geometries both at the general and detailed level of metal sheet shells and folded plate structures. New approaches like Off-Knot-Design combined with digital taxonomy and parametric tools provide a new way to design frame, truss, or beam-like structures from raw wood parts. Material design principles and the use of symbiotic biological properties help develop fungus and wood composites that can be disposed without further post-processing. The shown approaches demonstrate how well-known materials such as metal sheets and old materials such as wood lead to innovative sustainable solutions through interdisciplinary knowledge combined with computer algorithms and tools.

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Keywords: metal sheet lightweight structures, self-tapping screws, mycelium composites, off-knot design, parametrical tools, raw wood design.

1. Approaches for a sustainable building design and building-construction

For a particular sustainable building design based on a minimized use of material or based on natural materials special technical approaches have to be considered and traced. For building purposes on one hand material must be available in mass dimensions and on the other hand, concerning the end of use, material should be totally recyclable or directly be brought back to the natural cycle. Materials must not be too refined just as much it is required due to production premises and processing. Materials which are just suitable at end of use for downcycling, like concrete and other artificial stone products, should be limited in use. Similarly, plastics, made from fossil oil, may not accepted as sustainable building materials. Wood as one of the oldest natural building materials in the northern climate zones of the earth was affordable to win and became typical for the rural and town architecture in these regions. Due to its insufficient fire resistance and resistance against biological attacks man started coating of timber elements, using chemicals to come over these problems. Chemically treated wood may not be brought back to nature without spoiling natural resources of soil and water. The technical strategy must include the development of biobased coating and protecting systems, in order to create fully bio-degradable timber-components, to be stored in nature without empoisoning it. And another part of a future sustainable technical strategy should be the development of biobased materials to be used as voluminous material producing walls, panels, insulation devices like e.g. mycelium-composites, starch-based composites and similar substances.

Steel, another common material in building construction, is, compared to others, a nearly fully recyclable one. It is strong with high performance in strength and load-bearing capacity and, therefore, preferably applicable to lightweight structures. Traditional steel construction is based on building-kit-like longitudinal element sections like I-, U- or hollow-sections and typed nuts-and-bolts joining details. Plate-girder beams, box girders, and spheric shells made from doubly curved steel plates, welded together, form contiguous building components for bridges and containers. Modern steel construction is based on individualized sheet-metal elements, used in the automotive and aeronautic design, where weight minimization is essential, and in building construction, where resource-saving is crucial. Sheet-metal element design allows the combination of structural and covering purposes and the creation of integrated stiff and stable structures.

2. Steel-Lightweight-Structures

Frei Otto (1925-2015) was one of the pioneers of tensile-loaded lightweight structures. Jean Prouvé (1901-1984) and Hugo Junkers (1859-1935) were pioneers in using sheet metal for buildings and housings. Concerning sheet-metal structures the introduction of tessellation systems for segmentation is essential to achieve structural efficiency and to allow prefabrication. Orthogonal structures out from sheet metal will be based on modular systems, 3D-bended folded or shell-like structures are based on topological order systems.

2.1. Self-supporting lightweight-building system from sheet-metal

Advanced CAD systems and parametric design tools enable us to describe any individualized three-dimensional curved shape and develop and detail it within the computer environment. Appropriate methods for subdividing ensure the realization of the virtual models of free-formed buildings. Modular order gives place to topological order, where parts agree in their general shape but not in their dimensions. Suitable structural principles for load-bearing sheet-metal structures must be developed [1].

2.2. Prototype 1

The Chair of Structures and Structural Design and the Institute of Metal Forming at Aachen University developed a building system for self-supporting sheet-metal shells and built prototypes to investigate the productional and statical potentials of the construction system as well as their applicability. Based on double-layered Fold-Core-Plates (germ: 'Faltleichtbauplatten') with a plane layer connected to a layer of hexagonal pyramids, providing bending capacity in three areal dimensions. The Prototype 1 'Flying Carpet' was developed based on Rhino-Grasshopper-scripts, where the complete geometrical information, also for the production of the individual parts based on Incremental Sheet-Forming (ISF), was extracted [2, 3]. Prototype 1 (see Fig. 1) consists of 140 hexagonal pyramid elements and 319 triangular plates, joined together at the folds by clinching and connecting the two layers with spot-welded threaded bolts and nuts. The whole production of the parts corresponds with a true File-to-Factory-Process.

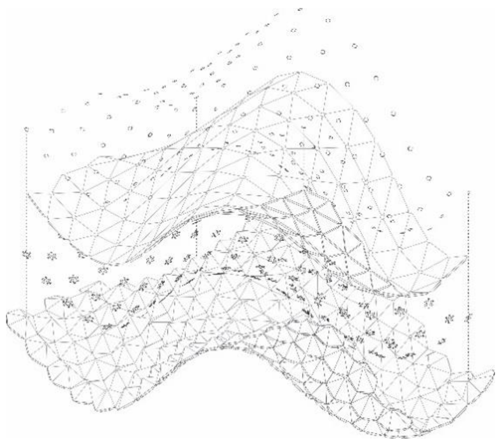

Fig. 1. Prototype 1 based on faceted plane components.

2.3. Prototype 2

As Prototype 1 has faceted surfaces, developing the process onto smooth surfaces was challenging. The ISF -procedure had to be developed and combined with stretch drawing. To extend the range of forms, a simple mold called 'Smart-Die' was introduced, which allowed the realization of smooth, three-dimensional curvature of panels. Instead, joints at the folded edge of the panels were connected by a layered joint, minimizing the joint gap, and supporting the continuity of the overall geometry of the prototype. Punched-in cones into the inner sheet metal take over the shear connection between both layers, replacing the pyramidal layer of the previous prototype [4, 5]. Prototype 2 (see Fig. 2) will soon be presented on the campus of RWTH Aachen as a pavilion.


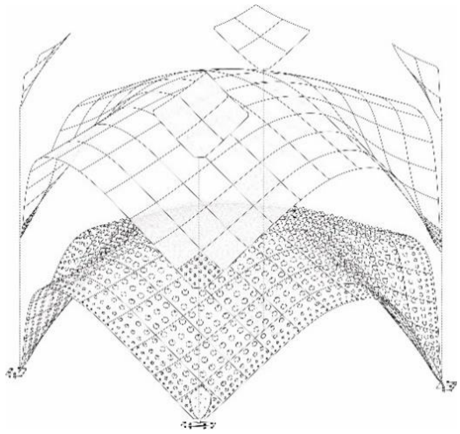

Fig. 2. Prototype 2 based on smooth sheet-metal components.

2.4. Prototype 3

The double-layer construction of the previous prototypes causes a significant effort. For specific purposes, just one layer of steel sheet metal is sufficient, e.g., if just a predominant load case is acting or if a steel-sheet-metal layer is part of a hybrid or composite system combined with a concrete shell above. The one-layer compression loadable membrane system consists of metal sheets with coined in star-like crosses arranged as a regular pattern, preventing local buckling (see Fig. 3) [6]. The inclined stars may overtake the shear connection by tight fit.


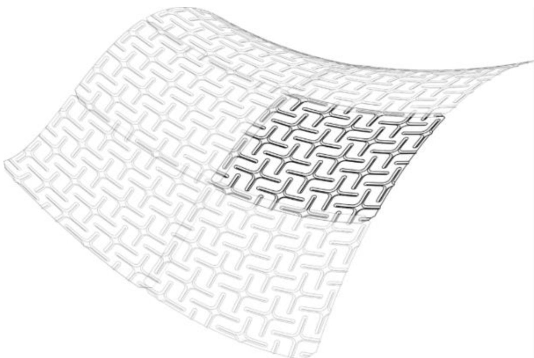

Fig. 3. Prototype 3 based on one-layer represents a pattern-coined compression-loadable membrane

3. Wood and natural materials

In the context of sustainability is wood design a very popular material. In the building construction context, it is traditionally applied according to its natural property in longitudinal components or as boards. Modern forms are glue-laminated beams or cross-laminated panels. A systemic disadvantage of wood is its anisotropic strength behaviour with high strength parallel to grain and a relative weakness perpendicular to it, with a negative effect on joints, especially with mechanical fasteners. On the other hand, biodegrading organisms process wood and produce hyphens that provide the ability to join wood parts that can be used for fully bio-based and new composite materials and wood semi-finished products.

Classical timber production is based on a selection of parts of trees like the stem, which causes a huge mass of waste to be processed into wood chips. Using glue, this is further processed to OSB-boards and other glue-based timber composites. Another way to deal with wood as it is grown, raw wood, is to use it as structural elements with minimized refinement.

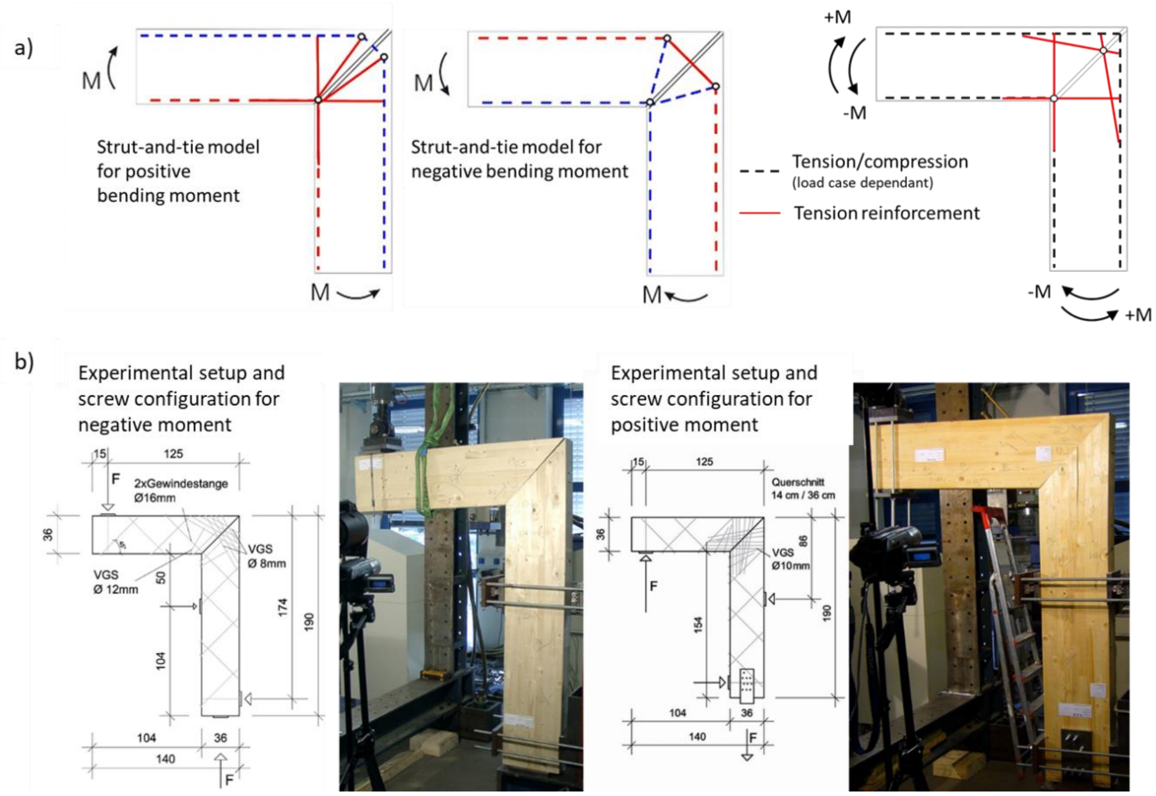

Fig.4: Rigid frame corner joint, realized with self-tapping-screws: a) simplified strut-and-tie modelling for the rigid frame corner; b) screw configurations and experimental tests of the rigid frame corners for positive and negative bending moment [7-13].

3.1. Beam- and truss-structures from glue-laminated components

Glue-laminated timber parts improved the structural applicability and potential of wood in the field of beam-, frame- and truss-structures. The systemic disadvantage of wood, the weakness lateral to grain, and the relative weakness of joints and mechanical fasteners, can be prevailed using self-tapping screws as joint elements and as reinforcement of highly stressed zones .

3.2. Reinforcing and joining timber components with self-tapping screws

Alike reinforced concrete the arrangement and the inner forces of timber reinforcement with self-tapping screws can be derived with the help of strut-and-tie models (Fig.4). Configurations of screws allow for to transfer of much more load over joints as conventional bar dowels and tin-plate joints [7-13]. Where concrete reinforcement is mainly induced to overcome tensile forces causing cracks, timber reinforcement may be introduced to influence the inner force flow of beams or other building components. The much higher performance in terms of stresses and stiffness of the steel screws compared to wood helps to overcome the poor stress performance particularly lateral to grain, also cross to the main force flow (see Fig. 5).

Fig. 5. Test specimen of reinforced timber

3.3. Raw-Timber Structures

Traditional timber production is associated with masses of wood waste that can only be partly reused for pre-products. The bulk of the wood remaining must be handled by forestry and vanish unused in nature. Naturally grown and unrefined wood may also be curved and include forks, which technically represent a very rigid joint of timber elements. To use those forks in a structural context for buildings and other structures, another way of constructing bar- and beam structures must be applied [14]. This method is the Off-Knot- Construction or Off-Knot-Design. It provides a design of bar and beam structures, where structural knots and joint are separated and connections between structural elements do not coincide with joints, but are translocated, 'offset' along the length of the structural elements (=> 'Off-Knot'). Off-Knot-Construction may be applied to steel construction, where the structural knots are prefabricated and welded together or may be applied to raw timber construction with natural wood parts, given in geometry and dimensions by nature, and joined together afterwards. Whereas traditional design of bar and beam structures unifies always structural knots with joints. Joining raw timber elements, metal or hardwood interfaces may be used. Designs with naturally grown timber needs other simulation methods and other methods of stress calculation as wood is structurally used as a whole with its natural polar sections of variable local stiffness and strength [15], [16].

Fig. 6. Object examples with raw timber: chair and connection of one arm and back of the chair

Fig. 7. Parts of a Raw-Timber-Truss with Off-Knot-Joints

3.4. Mycelium Composites

Wood is a ubiquitous material in many parts of the world, and nature has developed fungus to redevelop its substances of it for reuse. Mycelium processes dead wood by penetrating it by hyphae, forming a felt-like spatial net. When inoculating mycelium spores into a wood chips or wood shavings substrate, the hyphae soak it, penetrating the substrate's single grain and binding the particles together. The mycelium composite arises from this process, a formable matrix material of chipped wood and fungi. Each mycelium species prefers coniferous wood or hardwood, on which the growth of hypha depends. Concerning mycelium composites' technical properties, combining wood particles and mycelium species is crucial [17], [18].

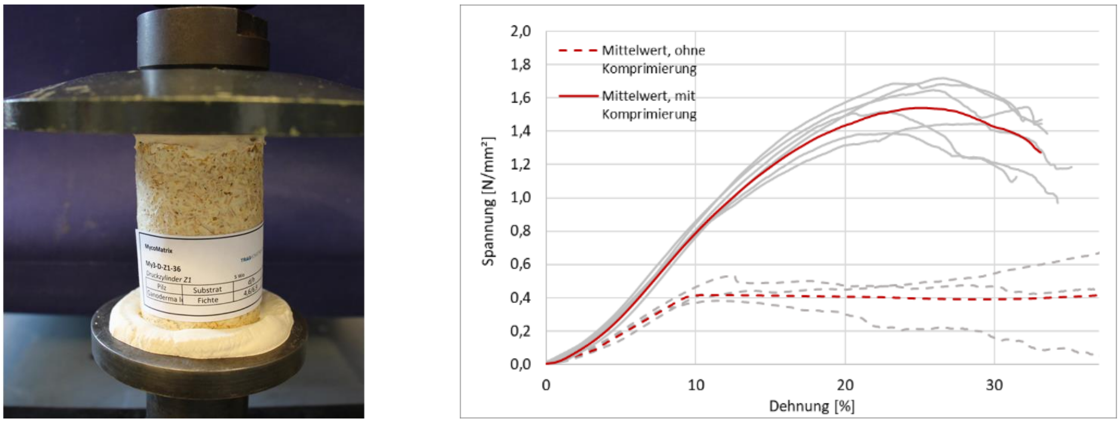

Fig. 7. Compression test of specimen of mycelium composite and load-deformation -curve.

3.4.1. Solid Building Structures

The mechanical strength of mycelium composites is moderate. It depends mainly on the substrate's wood species, the process-related treatment of the material, and the mature time provided for the transformation process. The strength of a standard mycelium composite is comparable to plastics like polyurethane (PU) or similar, which applies to lower-stress structures like solid buildings, masonry, and sandwich structures [19].

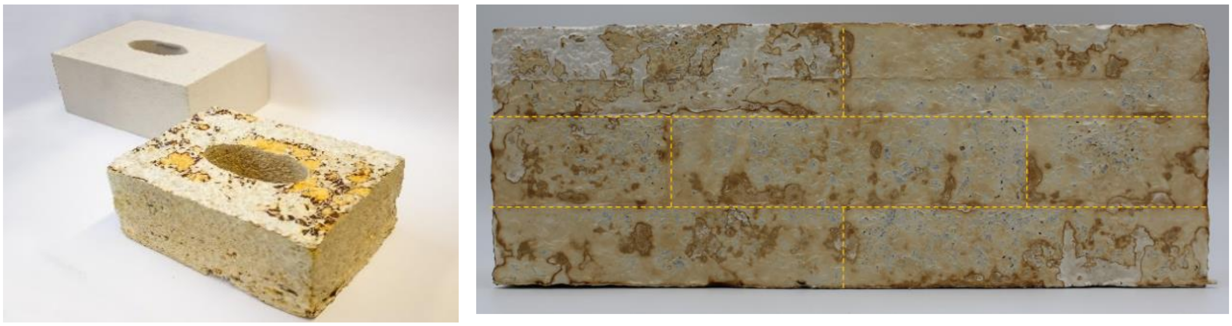

Fig. 8. Masonry-Stone and part of a brick-wall made out from mycelium composites.

- Masonry Systems

The mycelium composite is initially a living material comparable to natural materials like yeast dough, adaptable to molds to form masonry-like components. The cultivation period plays a crucial role in achieving the required strength, and it also depends on the mycelium species and the grade of transformation of the wood grain or chips. After this period, the mycelium composite will be denatured to stop the growth process and the further development of fungi. This procedure makes it possible to use the systemic advantage of living materials: as long as the bricks of a mycelium composite wall are not denatured, they keep growing and growing together, and the arising wall is – after an additional growth period - fully coherent. Mycelium composite masonry does not require additional mortar and is a homogenous natural material to be disposed of without adverse environmental consequences.

- Sandwich Structures

The binding capacity [20] of mycelium composites to wooden materials is also combined with timber boards acting as shuttering on either side and forming a Sandwich element. This may be used as wall panels or slab components within building systems, including bar and beam components, combined with self-tapping screws as the only non-biological part of this system [21].

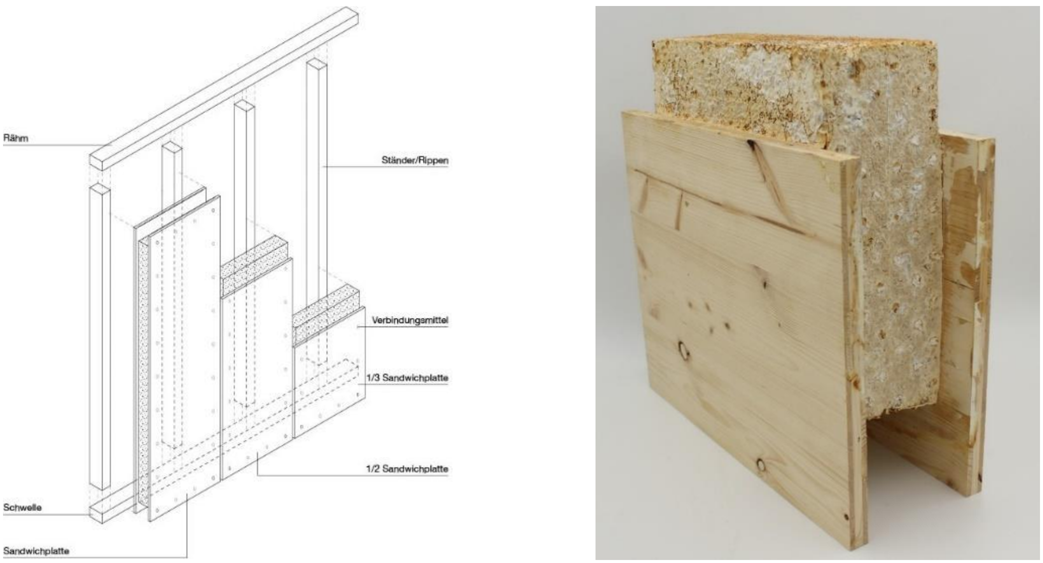

Fig.9: Sandwich – wall system with timber boards and a core of mycelium composites.

4. Resumée

Sustainable future architecture and structural engineering will not be represented only by high-tech structures and architecture with glass, steel, and plastics but also – because of a growing lack of resources – by innovative sustainable technical approaches with material saving techniques and advanced bio based materials. The progress in computer methods concerning analysis, simulation of structures, and parametric design and highly effective computer tools for scanning, processing, and archiving of 3D data as well as comprehensive biological knowledge, offers innovative methods and tools of analysis, development, and creative work. They allow innovative approaches and may be applied either to the design of material efficient and individualized structures or to develop or to brush up archaic, nature-based building techniques. It will be a matter of time until this mindset will overcome the image of fashion and become a common attitude to deal with building, structural engineering, and architecture.

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