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Reimagining Design for a Light Environmental Impact: The Paper Composition Pavilion

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Abstract
The lightweight design philosophy has always stood for efficient use of materials and elegant structural design. Lightweight materials provide visual lightness but are not necessarily recyclable. In this publication we present a new demonstrator for circular lightweight structures that explores and redefines the design characteristics of lightweight structures. Lightness is understood here not only in terms of weight, but also in terms of environmental impact. The parametric design develops a forward-looking approach to lightweight structures based on material cycles, using paper as an alternative building material. The structural potential of the developed composite modules, consisting of folded paper, is tested for mechanical properties. In combination with cables to create a hybrid lightweight structure, the pavilion is then analysed concerning its environmental impact and circularity. As a temporary structure, the Paper Composition Pavilion, designed by architecture and structural engineering students as part of the IASS WG21 competition, embodies a new vision of sustainable lightweight concepts and invites reflection on the redefinition of responsible design in engineering to respond creatively to changes in the construction industry.

Keywords: research pavilion, circular economy, lightweight structures, sustainability, alternative building materials, temporary architecture, paper

1. Introduction

1.1. Background
As a design philosophy, lightweight structures have always embodied the idea of efficiency. An optimised design language makes it possible to create structures that require less material and at the same time make optimum use of the materials used. High-strength and weight-optimised materials also contribute to a filigree and lightweight appearance.

The demand for this lightweight appearance has recently led to a strong focus on high-performance composite materials in lightweight structures. Although these materials fulfil the technical requirements of their intended use, their recyclability must be viewed from a critical perspective. Many composites used in lightweight structures are a symbiosis of individual materials that cannot be separated by type at the end of their life in the product or suffer a loss of quality due to downgrading.

Due to the growing climate crisis and the scarcity of resources, solutions to these problems are increasingly being sought in the construction industry, which is largely responsible for these issues

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(United Nations Environment Programme [1]). A material that can fulfil these modern principles of sustainability is paper. It is made from renewable organic raw materials or obtained by reusing old materials. This makes it biodegradable, helps to bind CO_2 and can also be used as a building material.

The use of paper in architecture is an up-and-coming field that is becoming increasingly important due to its ecological benefits. Knaack et al. [2] even describe the use of paper as "a kind of wood 2.0", as it represents the further development of the renewable raw material wood, which is also currently experiencing a renaissance.

One challenge when using paper in structures is its durability, especially in applications that are exposed to the weather. Resistance towards such conditions was recently investigated by Bach [3] in a dissertation. Jasiołek et al. [4] also investigated biodegradable coatings to make paper usable as a building material.

As paper is easy to fold, the use of origami folding techniques for structural applications is also being researched, as folding gives the thin-walled shell structures greater rigidity (Knaack [2]). For this publication, the work of Richard Sweeney [5] has served as a source of inspiration for the new, organic, and modular way of folding.

Prominent examples of paper in architecture are the works of Japanese architect Shigeru Ban, who introduced paper tube constructions into architectural practice in the 1980s (Łątka [6]). One of his largest projects is the Expo Pavilion in Hanover in 2000, for which Frei Otto acted as an architect consultant (Detail [7]). The connection to lightweight structures becomes clear here.

A responsibly designed lightweight structure should also contribute to a sustainable environment. The use of paper is seen as having great potential, not only because of its visual lightness, but also because of its ecological lightness. Although paper has already been successfully used as a building material in smaller, temporary pavilions (Jasiołek [8]), what is missing is an examination of building with paper from an aesthetic perspective.

Every building material brings with it new design rules in its constructive realisation, as the design and manufacturing processes differ. In the field of lightweight paper construction, there are currently few standard solutions and no standards that bring this new type of building material into a set of rules. The scope for architects and engineers to redefine the design possibilities and emerging structural aesthetics is therefore particularly large here (Knaack [2]).

1.2. Research objective

In this publication, we present a novel demonstrator for circular lightweight structures that explores and redefines the design characteristics of lightweight structures. Lightweight structures are understood here not only as light in weight, but also as light in their environmental impact. How light do lightweight structures have to be to meet today's challenges in the construction industry?

The computer-aided, parametric design takes up this question and develops its own approach for the future of lightweight construction, which is based on circular materiality and detachable components. Paper serves as an alternative construction material, which is to be used based on origami folding techniques. The mechanical properties of the developed components will be analysed in experimental tests. A thorough investigation of the environmental impact and the circularity of the developed solution is also part of the research.

The resulting interdisciplinary pavilion, which was developed by architecture and civil engineering students, will be exhibited as part of the WG21 competition and, as a temporary structure, will demonstrate a new vision of sustainable lightweight structures.

2. Design of the Paper Composition Pavilion

The competition design is characterised by the interdisciplinary approach between architecture and structural engineering students at HafenCity University Hamburg. The special focus of the design lies in the use of paper as a sustainable material as well as detachable connections of the overall structure, ensuring that the pavilion responds to a necessary transformation to a circular economy. The second question that the pavilion explores is the extent to which paper as a material can contribute not only to lightness in weight, but also to lightness in its environmental impact. The iterative design process takes the complicated interaction between strength, form, and material into account. The name Paper Composition alludes to the composite material paper, which is also used in its composition to create a design effect.

The IASS WG21 competition conditions specified that the individual modules could be transported as checked baggage in a maximum of six boxes on an aeroplane. This posed challenges for the structure, leading to the decision in favour of a modular design to ensure easy disassembly. Paper as a raw material is extremely light and can also be moulded into the desired shapes on site.

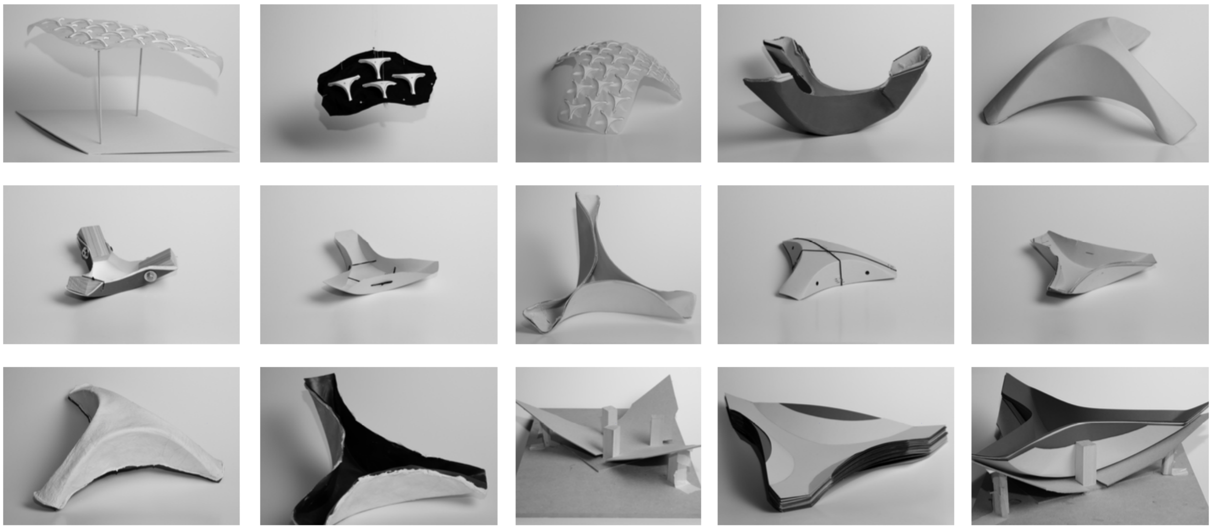

Figure 1: Study models in the early design process.

The first preliminary studies of the developed concept are shown in Figure 1. Due to the materiality of the structure, the designers worked early on with smaller physical models made from paper, cardboard, pins, and nylon fabric. As the load-bearing behaviour can already be read on a small scale, the model studies enabled design variants to be favoured and pursued, but also excluded.

A large part of the design work involved experimenting with paper and cardboard and researching origami folding techniques. A three-dimensional single module that can be assembled into larger structures was developed using origami principles. The initial idea was a double-curved paper shell module. Figure 2 shows the folding mechanism: Starting from a flat, triangular basic shape, the sides are first cut in a circle and then folded at the same angle and folded inwards. This creates stiffening ribs in the modules. To form coherent patterns, these are then coupled together in an alternating pattern. An inverted module (shown here in red) is connected to three modules in their original position.

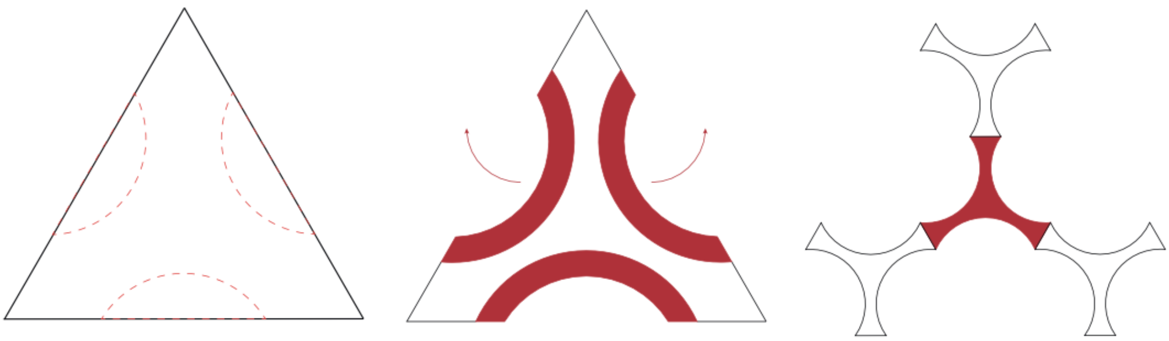

Figure 2: Folding mechanism.

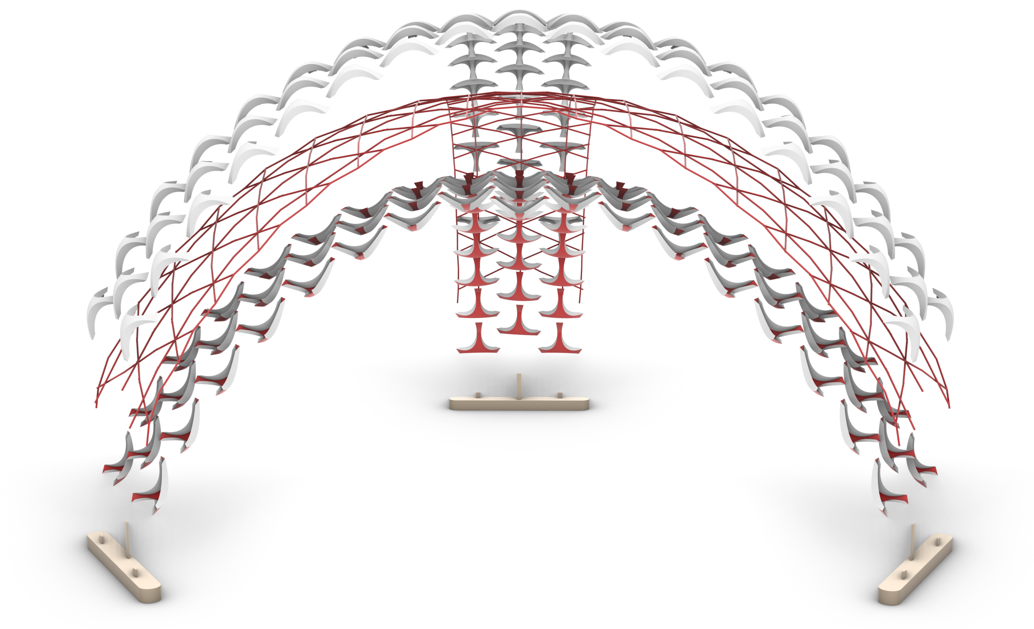

Figure 3: The Paper Composition Pavilion.

In principle, the still flat layer formed in this way can now be moulded into a variety of shapes, but the principle can only develop a structural effect in combination with a second, mirror-inverted layer and a tensile component. In the configuration shown, the structure consists of several modules, which are arranged in a purely normal force stressed shell with three support areas. At each of the support points, three modules in a special wooden base construction transfer the dead weight and other occurring loads to the ground. The overall shape of the pavilion structure thus echoes the shape of the individual modules.

Simplified, the modules function as a three-dimensional truss system, whereby the normal forces are not transmitted via straight elements, but via curved, compressive shell elements within the structure. The curvature is achieved by varying the module sizes of the upper and lower layers. To fix the paper modules in their curved position and to ensure the load-bearing function of the overall structure through pre-tensioning, cables made from hemp are positioned between the two module layers. These cables are arranged in parallel rows. Overall, a fragile balance is created between compression and tension elements in the pavilion structure.

The connections between the alternating curved paper modules are created using small pieces of wood inserted into the webs. These form a dovetail joint so that the modules interlock with each other using a form-fit connection. The tensioned cable runs through the joint and is clamped into position. Force transmission is achieved by using only the outside of the paper modules and not the folded inner ribs.

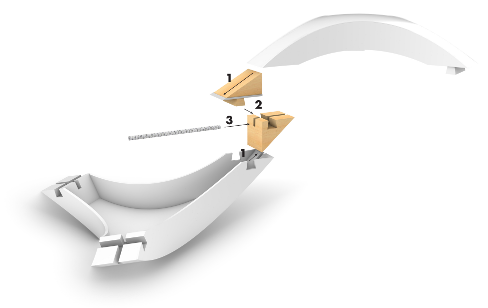

Figure 4: Connections between modules.

A single shell module is created by folding several layers of paper to achieve greater rigidity. The particular challenge lay in creating the bond between the layers, which had to be as shear-resistant as possible. This revealed an interplay between weather resistance and the type of construction.

Many of the ideas considered in the design process for retaining the folded paper layers in their new shape allow water to penetrate through the outer skin of the modules through punched holes or screw connections, which could compromise the outdoor structure. Gluing the individual papers together, on the other hand, was not desirable due to the non-circulatory nature of the glues. In the end, the decision was made to coat the outer paper layer with beeswax, which is both water-repellent and biodegradable.

3. Research findings

To further develop the outlined concept, the individual modules were first optimised in terms of their load-bearing capacity and subjected to load tests. The desired final shape was then transferred into a parametric design and evaluated in terms of its environmental impact and circularity. Finally, the construction of a mock-up verified the load-bearing capacity and analysed the challenges of the construction process.

3.1. Development and optimisation of the individual modules

The folding method essentially determines the load-bearing capacity of each individual module. The starting point for the development was a relatively flat fold without partial cutting of the side ribs (I). However, this restricts the strength of the curvature of the module. By reducing the ribs, a higher curvature could be achieved (II). In addition, the folding curve was placed closer to the high point of the shell (III). Finally, the ribs were reduced to such an extent that the side edges of the modules touch each other under vertical load, creating additional rigidity (IV).

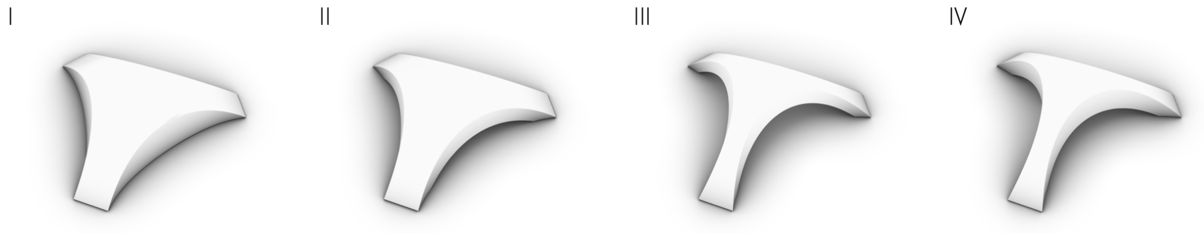

Figure 5: Optimisation of the individual modules.

3.2. Load tests

The preliminary load tests on the individual paper modules were carried out in the relevant load direction parallel to the base plane of the shell structure. By gradually applying weight, the resulting deflections could be measured until plastic failure. The results proved that the pavilion reaches a maximum of 37% of its ultimate load-bearing capacity under dead weight.

3.3. Parametric model

The parametric Grasshopper model depicts the research pavilion in a possible arrangement of the individual paper modules.

The development and optimisation of the modules described above is also reflected in the model: the algorithm begins with the design of the modules, whereby the web width, the curvature intensity, the folding depth, and the span of the individual modules can be controlled parametrically. In subsequent steps, the primary structure of a shell is then formed, on which the modules are then positioned. The module sizes vary slightly depending on their position on the overall structure to achieve the desired curvature.

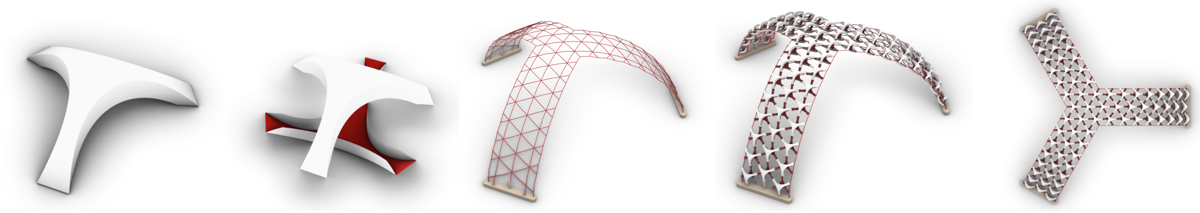

Figure 6: Parametric design process.

3.4. Assessment of environmental impact and circularity

The pavilion is mainly made of renewable materials and can be easily dismantled into its various components. All individual parts are bolted together and can therefore be easily separated again to move or dismantle the structure.

While the renewable materials can all be returned to the biological cycle, the small quantities of steel used are taken from the technical cycle. Here, a higher energy input is to be expected for recycling, but the steel parts are not damaged during this process, hence they can be directly reused in new applications.

The organic materials hemp, wood and paper can also be reused and composted. Beeswax, which is used to coat the paper modules, has a special function here. This can also be reheated and reapplied depending on how long it has been in place, providing a circular solution.

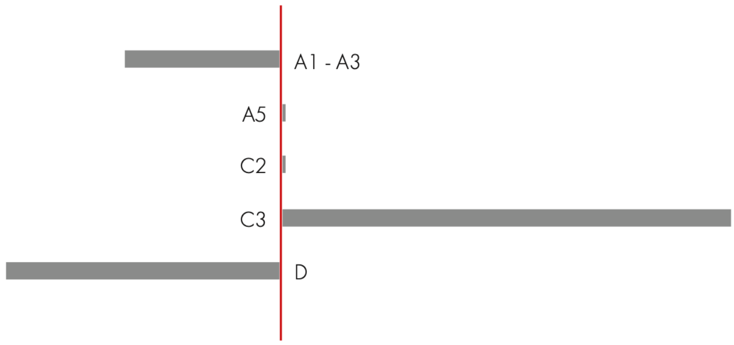

Figure 7: Life cycle assessment.

The computer-aided model was used to determine precise material quantities, which in turn were used for a life cycle analysis following EN 15804. Figure 7 shows the global warming potential of the pavilion structure in $kgCO_2$ equivalents. In the configuration shown, the impact of both the manufacturing phase (modules A1-A3) in combination with the high potential for reuse, recovery and recycling (module D) almost counterbalances the waste processing (module C3) due to the large amount of organic material used, resulting in a total of only 1.05 $kgCO_2$ equivalents.

3.5. Mock-up

To verify the feasibility of the proposed design, a 1:1 scale mock-up was built showing a section of the overall structure (Figure 8). Instead of the proposed cables, this model tested load transmission through a textile membrane. Various light studies show aesthetic and visual qualities of the design. The transparent appearance of the thin cotton fabric stretches delicately between the changing compression elements made of paper composite.

The manufacturing process of the individual modules is shown in Figure 9. After being cut out, the individual modules were manufactured using a press, which is a scalable and fast process. The wooden inlays were then cut to size and the paper modules prepared for the fasteners. Finally, the modules were attached to the tensioned membrane at the intended points.

Figure 8: Mock-up of the structure.

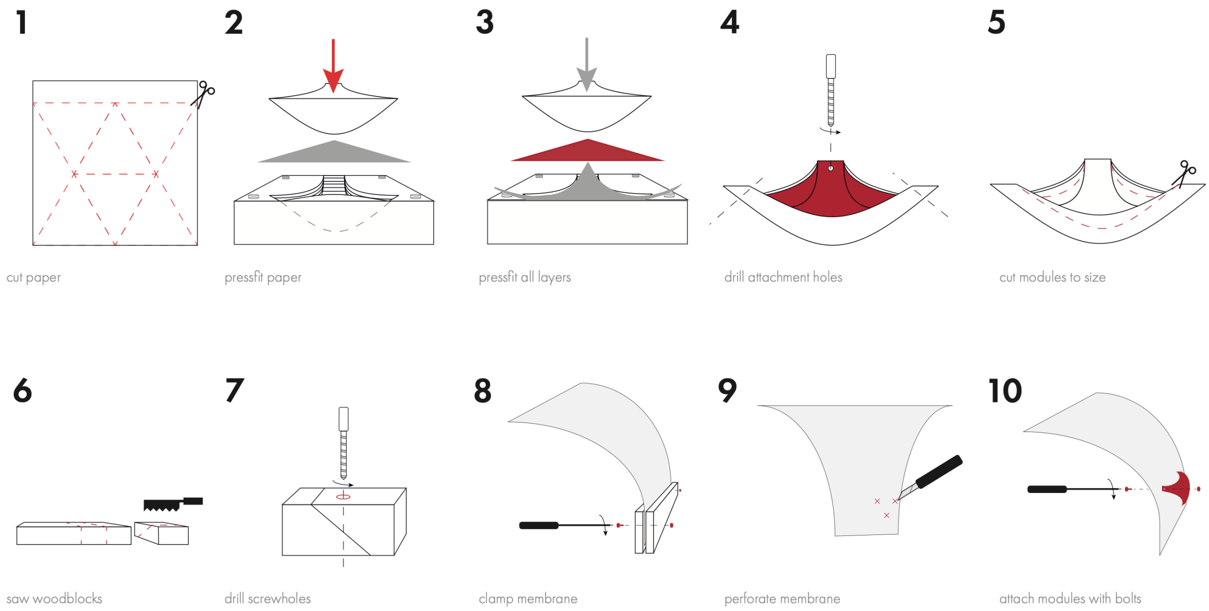

Figure 9: Manufacturing process of the mock-up.

4. Discussion

The delicate and light appearance of building with paper opens up an exciting field of design. The question of how lightness has an aesthetic effect, particularly in combination with ecological aspects, formed the core of the investigated concept. Experimenting with paper as a building material not only enables visual lightness, but also represents a sustainable alternative, as the assessment of environmental impact and circularity reveals. In addition, the modular design makes it easy to assemble and dismantle the structure. Nevertheless, there are several starting points for further research that will be carried out before the final structure is built.

On the one hand, this concerns the numerical modelling of the interplay between the pavilion's compression and tension elements. As the static system only functions through the exact balance between the two elements, it is essential to determine the form. The preliminary studies developed so far, and the mock-up show the feasibility of the system in principle, but this should also be demonstrated on the numerical model. Here, the parametric design in Grasshopper offers great opportunities for optimising the global load-bearing behaviour. In addition, the optimised distribution of the differently sized modules can be derived from the numerical simulation.

There is also scope for optimisation with regard to the detailing and connections of the pavilion. As already mentioned, the form-finding process, especially for the cables, plays a major role. There is potential here for research into different types of material fibres, which then have to be cut to fit the respective loads. Their connection to the paper composite modules is realised using clamps between inserted slender pieces of wood. These can also be further refined to meet visual requirements.

The materiality of the paper itself is also the subject of further investigations. Whilst initial tests on the circular coating with beeswax have been successful, many options are still open with regard to the choice of the exact type of paper from which the composite is to be produced. These are to be researched in further steps, for example by testing the weather resistance of the paper composite outdoors. The optimised paper composite modules will also be subjected to load tests in the construction laboratory in order to precisely determine their mechanical load-bearing capacity.

The construction of the mock-up has already verified that the construction process works in principle. In particular, the erection process with the tensioned cables will be decisive for achieving the overall geometry. By optimising the material, the module structure and the connections, it is likely that this will still undergo changes.

Overall, in addition to aesthetic aspects, the presented research pavilion also emphasises the question of the durability of constructions. How important should the criterion of durability be in the construction industry? To date, the paradigm of maximising the service life of less recyclable materials and components has prevailed. However, the approach of ecological sustainability can also lead to a different way of thinking, in which the replaceability of components is emphasised and temporary use of recyclable materials with a shorter service life is also permitted.

5. Conclusion

While the lightweight design philosophy has always embodied the idea of efficient use of materials and thus decisively characterises the design of structures, the use of composite materials that are difficult to recycle questions the ecological lightness of lightweight structures. In this context, the use of paper as a building material can be advantageous both in terms of its lightweight aesthetics and its low environmental impact.

In this paper, experimental and computational techniques were combined to design a research pavilion. Firstly, a folding technique for paper was developed in preliminary studies, with the help of which large paper composite modules could be produced, which are supplemented by appropriate connections and in a combination with cables to form a hybrid structure. In this case, modularity includes the ability to remodel and reuse the entire structure in new contexts and applications. The further development of the designed concept showed a wide range of optimisation possibilities, which concern the optimal arrangement and size of the modules, but also include the global structural behaviour as well as mechanical and physical load tests.

The proposed design can be understood as a triad of lightweight structures: The pavilion is light in the truest sense of the word, as it uses very little material thanks to its open structural form. It protects the environment as it is mainly made from renewable raw materials and is virtually carbon neutral. It can be easily broken down into its components and reused in a cradle-to-cradle process. And finally, the modular design of the pavilion minimises the workload when assembling and dismantling it.

To summarise, the use of paper as a building material in lightweight structures, which has been little researched to date, offers a wide range of potential. The material-orientated design opens up new possibilities for the design language, as specific construction solutions have yet to be developed. The Paper Composition research pavilion invites visitors to reflect on the role of design in lightweight structures and its impact on ecology, without ignoring technical constraints such as form finding and optimisation. Redefining design is an exciting challenge for the creative minds of engineers, and one they must meet as climate change and scarce resources continue to challenge our world.

Acknowledgements

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