Form-Finding and Design Potentials of Bending-Active Plate Structures

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Abstract

This work presented investigates the form-finding and design potentials of bending-active plate structures. Using two reference projects from the recent past, the authors present different design methodologies that either follow a geometry-based or integrated approach. A closer look at the newly accessible tools for digital form-finding and analysis reveals their increasing importance for the design process. In order to better demonstrate their potential, the authors present three case studies, which each separately enhances the integrated approach and in combination indicate the existence of a much larger design space of bending-active plate structures.

Introduction

Bending-active plate structures use the elastic deformation of planar, off-the-shelf building materials to generate curved surface structures (Knippers et al. 2011). While the traditional maxim in engineering is to limit the amount of bending in structures, this typology actually harnesses bending for the creation of complex and extremely lightweight designs. In the past, thin plates have rarely been used as primary structure in architecture because of their low bending stiffness. Many sheet materials like plywood, metals, plastics, and fibre-reinforced polymers, however, are not only flexible but also have high tensile strength. The two properties together are a perfect match for bending-active structures because they enable elements to undergo large elastic deformations and to resist high stresses before failure. This behaviour opens up new possibilities for the design of bent static and kinetic structures (Lienhard et al. 2014; Schleicher et al. 2015). The most significant advantage of these systems is that they can be constructed from simple planar parts, which can be fabricated with inexpensive, conventional flatbed processes. Additionally, the assembly of

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these structures does not require skilled labour or auxiliary formwork. Despite these benefits, the design of bending-active plate structures is a major challenge. This is because it is difficult to assess their structural behaviour and to accurately anticipate their deformed geometry. Therefore, it is essential to develop new design approaches.

Design Approaches to Bending-Active Plate Structures

A recent study identified three main strategies for the design of bending-active structures. These are behaviour-based approaches, geometry-based approaches, or integrated approaches (Lienhard et al. 2013). Bent huts and tents of vernacular architecture, for example, fall into the first category. Here, bending is used rather intuitively during the construction process. While this first approach relies heavily on experience, the other two categories are more scientific and require experimental and analytical form-finding techniques. Their similarities and differences are illustrated by the examples of Buckminster Fuller's plydomes and the 2010 ICD/ITKE Research Pavilion (Figs. 1 and 2).

Fig. 1 Two-frequency geodesic plydome in Des Moines, Iowa, 1957. The hemisphere spans 7.3 m and is made out of marine plywood sheets with a thickness of 6.4 mm. (Marks 1973, p. 210)

Fig. 2 ICD/ITKE research pavilion 2010 spans 10 m and consists of 80 birch plywood strips with a thickness of 6.4 mm

Self-strutted Geodesic Plydomes

As part of his research on geodesic dome structures, Buckminster Fuller (1895–1983) experimented with various structural systems and materials. His motivation was to find an optimum balance between a structure's stability, weight, and cost (Marks et al. 1973). While the majority of his larger dome structures are triangulated lattice shells that use steel struts as structural framework and solid panels or textiles as cladding, some of his smaller projects investigated different structural typologies that further increased the efficiency of the systems. Of particular interest are the geodesic plydomes that he developed from the fifties on. Here, the key idea was to construct a dome-shaped enclosure through repetitive tiling of rectangular plywood sheets. Plywood sheets were used because they are mass-produced, easily obtainable, relatively inexpensive, and can be stacked compactly for shipment. Fuller used a geometry-based approach to fit the flat sheets to the doubly curved surface of a sphere. This approach is described in Fuller's 1959 patent for the system (Richard 1959). He first approximates the target geometry of a sphere with a regular polyhedron (Fig. 3a).

Next, he arranges individual plates along the edges of the polyhedron (Fig. 3b). Adjacent

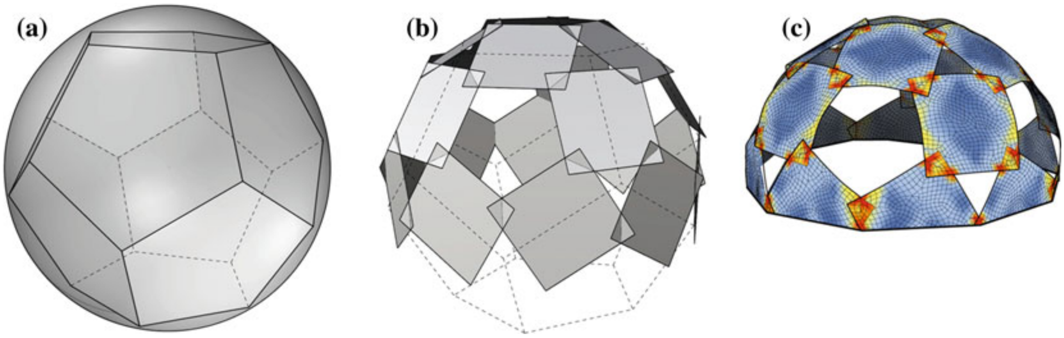

Fig. 3 Geometry-based approach of a plydome approximates a sphere with a polyhedron (**a**). Based on the polyhedron's edges multiple sheets get to arrange spatially (**b**) and then bent and fastened together (**c**)

plates are partially overlapped, pulled together, and fastened to one another with pre-drilled holes. This generates the double curvature of the global geometry even though the individual plates only experience single curvature at any given location (Fig. 3c). The greatest challenge in implementing Fuller's system is determining the amount of overlap between adjacent sheets and the location of the attachments points. Both are dictated by the deformed geometry of the plates and may also vary according to the sheet's position in the overall pattern. Without the digital tools that we have today, Fuller was forced to compute this information mathematically. Over time he calibrated these numerical results to the actual behaviour of the system.

ICD/ITKE Research Pavilion 2010

A good example of a more advanced approach to bending-active plate structures is the ICD/ITKE Research Pavilion 2010 (Fig. 2). This pavilion, which follows an integrated approach, was designed and built by students and teachers at the University of Stuttgart, as a collaborative effort between the Institute of Computational Design (ICD) and the Institute of Building Structures and Structural Design (ITKE) (Lienhard et al. 2011; Fleischmann et al. 2012). The project achieves a more complex curved geometry by alternating segmentally bent plywood strips that are linked together. The team began the design process by considering the limiting material characteristics of the plywood strips. The first step was to calibrate finite-element simulations with physical experiments. This ensured that the digital form-finding techniques provided an accurate description of the actual material behaviour while at the same time offering full control over the geometry. Of particular importance was the ratio between the pitch and span of a bent strip (Fig. 4a).

This ratio describes the maximum achievable deflection under a given safety factor. Once established, the ratio informed a parametric model that was used to design the global geometry of the pavilion (Fig. 4b). This model determined the dimensions and connection logic for each strip. The last step was to translate the geometry from the parametric model to a more advanced finite element analysis, which re-created the bending process under consideration of relevant material properties for birch plywood (Fig. 4c).

This last step was of key importance because it provided precise information about the pavilion's deformations and structural performance under different loading scenarios as well as essential data for the subsequent fabrication and assembly.

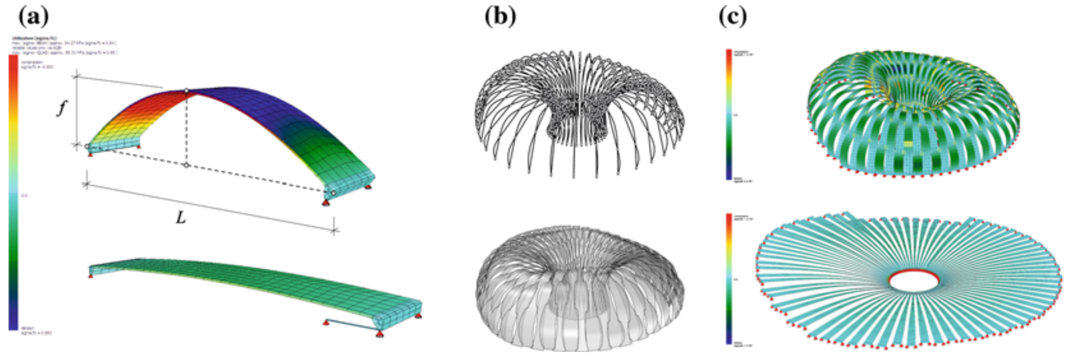

Fig. 4 ICD/ITKE research pavilion 2010 illustrates an integrated approach to the design of bending-active plate structures

Form-Finding and Analysis of Bending-Active Plate Structures

The biggest challenge regarding bending-active plate structures is the difficulty of predicting their deformed geometry and structural performance. As demonstrated by previous projects, options for their form-finding and analysis include physical modelling, mathematical calculations, and advanced digital simulations. These digital simulation tools, however, have only been available for a few years to a broader public. They can be subdivided into two categories:

The first method relates to real-time physics-based simulations. These are used extensively in the computer graphic community and are now also available for common CAD environments. The Rhinoceros® plugin Kangaroo Physics is a good example of this type of software. For the simulation of the bending behaviour of shells, it employs a discrete shell flexural energy model as described in Grinspun (2008) and Piker (2013). Mesh deformations are computed employing a dynamic relaxation scheme, requiring the introduction of lumped mass values and damping coefficients in the computational model. During the simulation process, the system converges to an equilibrium position that represents the final bent geometry. Although the definition of such additional parameters (mass, damping coefficients) is often arbitrary and not physically motivated, the strength of this computational scheme relies on the calculation speed and easiness of setup. This makes it ideally suited for iterative studies in early design stages or design explorations for structures with many elements.

The second method relies on finite element simulation (FEM). While this technique was originally used mainly for post-design analysis, non-linear FEM routines have advanced so much over the last few years that it has become practical to integrate them early in the design process (Lienhard et al. 2011). Programs like SOFiSTiK®, for example, allow a designer to calculate the deformations and stresses of structures under large deformations and to predict complex equilibrium states. In doing so, the software simulates the bending of a structure by considering both external forces and internal material stresses. Considering both simultaneously is particularly important because the geometry of a deformed structure depends significantly on the balance of forces that are exerted on it. Unlike real-time physics simulations, FEM can be also used to visualize the evolution of stresses within the material during the form-finding process. FEM simulations offer the most complete and correct mechanical description of the behaviour of shell elements, representing an invaluable tool for the correct evaluation of the mechanical behaviour and structural capacity of bending—active structures. On the other hand, the completeness

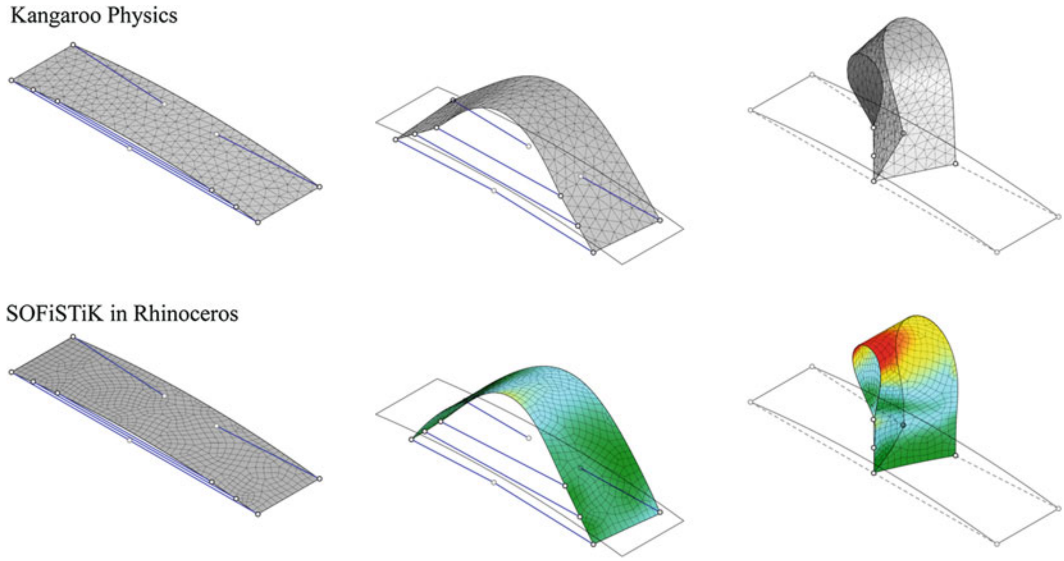

Fig. 5 Form-finding with contracting elastic cables using Kangaroo Physics and SOFiSTiK

of the mechanical model does not come for free, as it is computationally more intensive and can be rather slow for large models.

Contracting elastic cables provide a practical method to induce bending in both of these digital simulation techniques (Fig. 5). The cables are shortened through a reduction in stiffness and a simultaneously applied pre-stressing load (Lienhard et al. 2014). Each cable is attached to pairs of nodes on one or multiple meshes. These nodes are pulled together during the simulation process, which produces a controlled deformation of the attached meshes. This technique is very versatile and easy to use because it does not require the input of an explicit nodal displacement path.

Case Studies that Render New Potentials

The authors conducted a series of case studies to enhance the previously described integrated approach. These case studies separately explore new design potentials but also build upon each other to generate more complex bending-active plate structures.

Case Study 1—Effective Pinching

The first example explores the benefits and opportunities of the single-curvature that typically results from bending thin plates. Unlike the reference projects, which primarily use cylindrical shapes, this case study explores the potential of conical bending (Fig. 6). It conceptualizes a triangular facade module out of initially flat panels and challenges the design process by investigating shapes whose cutting patterns are not predefined from the start but needed to be determined through a series of simulations.

In this example, internal openings are pinched together to provoke global deformations in a plate. Material is strategically removed from the sheet's centre and the internal edges are forced together with contracting cables in Kangaroo Physics (Fig. 7a). This leads to a conical out-of-plane buckling that gives the plate a unique developable form. Each plate is then mirrored, merged, and trimmed with its counterpart, which brings about first changes to the initial cutting pattern (Fig. 7b). The result is a dual layer module with two plates that affect each other in form and significantly enhance the structural rigidity of the system. Trimming the

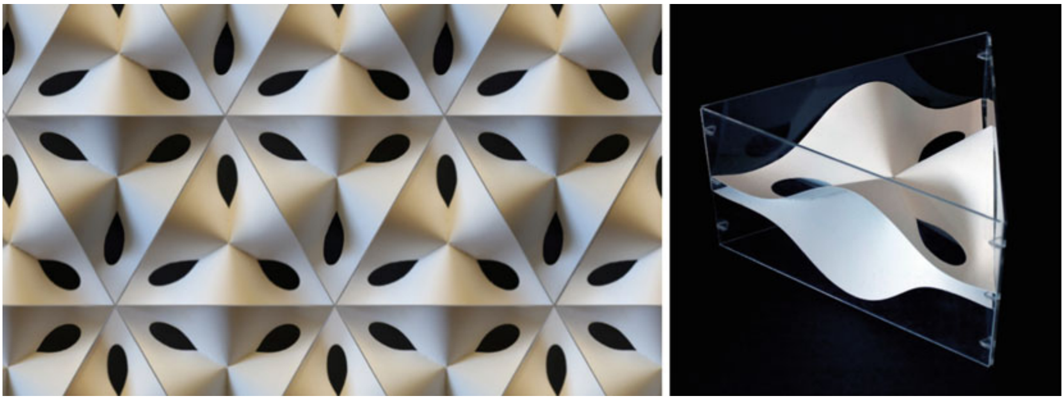

Fig. 6 Triangular facade tessellation with a module that is based on pinching and cross-connecting two thin sheets

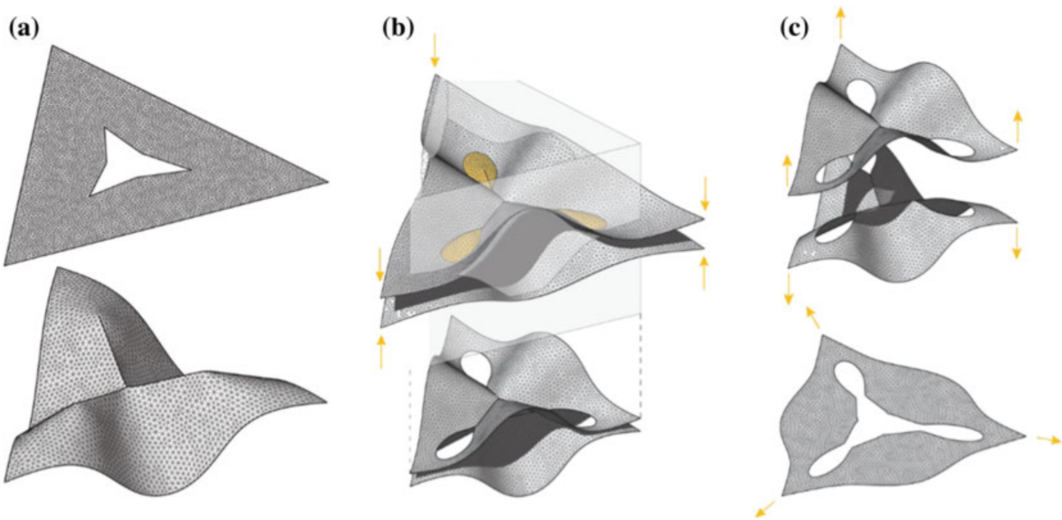

Fig. 7 Pinching a plate in the centre causes a conical deformation (**a**). Two plates can be merged with each other and trimmed (**b**) in order to derive with a special informed cutting pattern (**c**)

module's periphery with an extruded triangular profile produces the second substantial modification to the initial pattern. This step is necessary to guarantee that the module will fit into a symmetric facade tessellation. What makes this trimming action so special, however, is the fact that it is conducted on a plate that is already deformed, which results in a unique cutting pattern. The surprising complexity of the final pattern becomes particularly apparent in the last step of the form-finding process, where the layers of the module are separated and flattened by applying a uniformly distributed load that presses the mesh against a virtual floor (Fig. 7c).

Case Study 2—Mutual Reinforcement

The second case study aims to push the research one step further and focuses not only on an individual model but also on the complexity of the global system. It explores the question of how flat plates can be bent into a doubly curved, multi-layered structure that is extremely lightweight and has a high load-bearing capacity.

Similar to a piece of corrugated cardboard, this project uses the technique of pleating to cross-connect multiple thin sheets in order to form an assembly that is more rigid than the sum of its individual layers. What is most special about this project, however, is that it transfers the idea to a doubly curved global geometry (Fig. 8). This is not an easy task because a continuous flat plate can only be bent into single but not into double curvature. In order to achieve the global double curvature, the individual plates are perforated with holes and slits. These perforations divide the plates into individual zones that can be bent differentially. The role of the perforations, therefore, is to liberate individual plate segments from the necessity to take on double curvature. Instead, the Y-shaped subunits are only single curved and can conform to different synclastic and anticlastic target geometries. Multiple surfaces are stacked, offset, and then connected to one another in order to lock the shape of the global geometry and to provide a load path through the structure. In this way, every hole in the first layer gets filled and structurally supported by the second layer. This process is repeated by adding a third layer and more layers can be added to increase the stiffness of the structure.

A series of physical and digital studies were used to design and test the structural system. Material tests were synchronized with FEM simulations in order to determine the limit of feasible deformation, which is dictated by the local stress concentrations in the material (Fig. 9a). An additional factor that had to be considered was the amplification effect that results from the interaction between the interconnected layers. This interaction was used to determine the degree of variation between adjacent perforation patterns (Fig. 9b). Once a feasible deformation for a given sheet material was found, it was possible to develop an abstracted parametric model that preserved the internal relationships of the system and limited the design space to achievable solutions (Fig. 9c). This approach required less computing power than a comprehensive FEM analysis and allowed for the efficient tessellation of various doubly curved surfaces.

Case Study 3—Functionalized Instability

The third case study builds on the insights of the previous two examples and explores bending

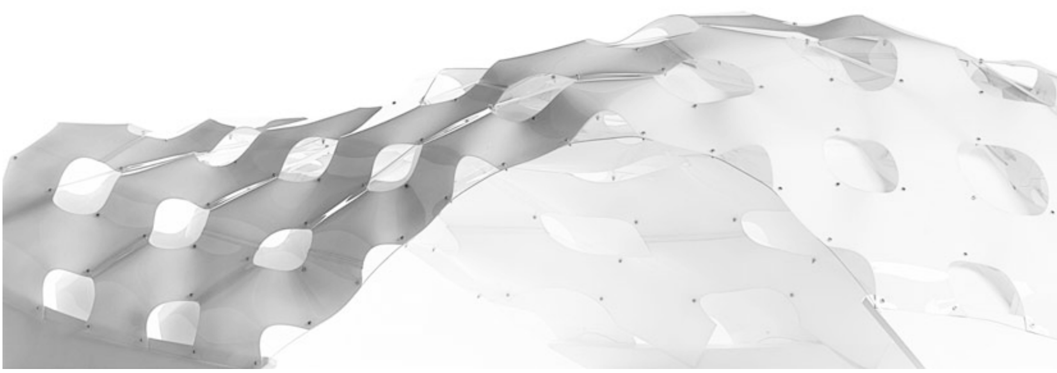

Fig. 8 Mock-up of a 2 × 1 m plate structure uses the coupling of three PET-G layers of 1 mm thickness to obtain a freeform geometry with a high load-bearing capacity

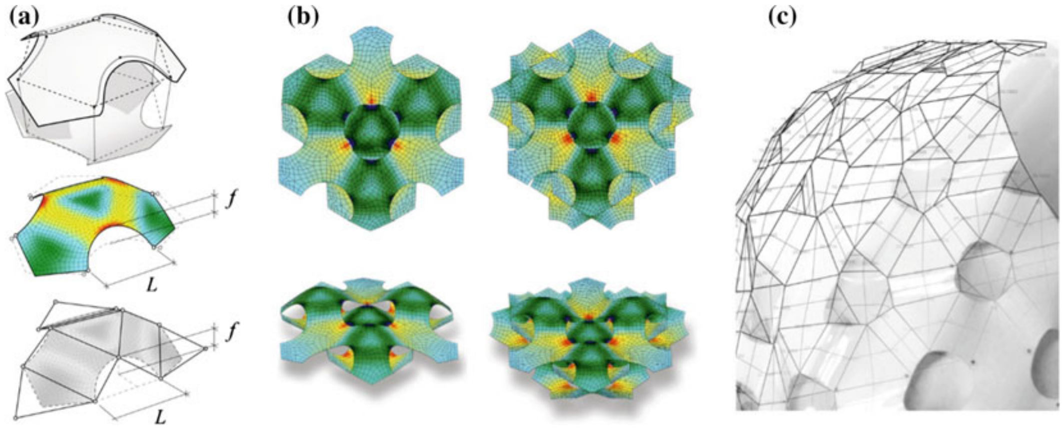

Fig. 9 Considering local stress concentrations in the individual unit as well as in the interacting layers, allowed to simplify the system to a parametric model with which to easily populate given freeform surfaces

both as a form-giving strategy and also as practical means to quickly assemble a larger structure out of multiple smaller subunits. It uses a snap-through instability mechanism to connect the components of the system.

Like the previous examples, this project restricts itself to elements that are constructed from flat sheet material. In this case, the structure is assembled from variations of only four basic shapes. These include two annular components and two longer undulating strips (Fig. 10). The components vary in size and edge conditions, and are fitted with mortise and tenon joints to connect adjacent pieces together. The annular components get pulled together at their ends to create conical frustums. These truncated cones fit precisely to the undulating strips and act as spacers between two layers in the system. Once all parts are loosely assembled, they are fastened together by pressing on the cones and deliberately causing them to buckle until they snap through to a new equilibrium position. This process is used to clamp adjacent parts and it is repeated three times to fully lock all of the structural components together. The result is a double-layered sandwich structure that is geometrically versatile and can be applied to both synclastic and anticlastic shapes (Fig. 11).

Fig. 10 The entire structure consists of four basic shapes that are clamped together by a local snap-through instability mechanism

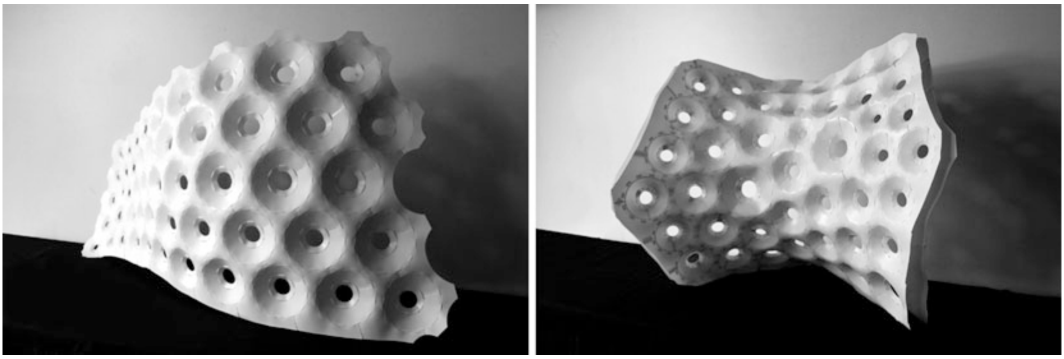

Fig. 11 This construction methodology can be applied to the design of synclastic and anticlastic surfaces

An important step in this project was to translate this construction method into a computational process that allows for morphological differentiation. In order to do so, an integrated approach was developed to incorporate both geometric and material constraints. FEM analyses were conducted at two different scales. At the level of the subunit, FEM simulations were used to determine suitable material characteristics and restricting geometric dimensions to ensure that the truncated cones can be snapped by hand. At the global level, FEM simulations were used to optimize the thickness of the sandwich structure depending on the stress distribution in the target surface (Fig. 12). Areas with larger bending moments have more distance between the two layers, while areas with higher shear forces have smaller cones and thus feature greater material density. This structural information was used to inform the packing pattern that was applied to the target surface. There is a direct relationship between cone radius, assembly thickness, and material density, which all act together on the final composition of the structure. Finally, the detailing and layout of the individual parts was automated in order to facilitate an easy translation to new global geometries. Each individual component is automatically unrolled and detailed with the mortise and tenon joints that are used to connect the parts together. As a proof of concept, a large-scale model was constructed using flatbed fabrication technologies and light PET-G plates of 0.5 and 0.75 mm thicknesses (Fig. 13).

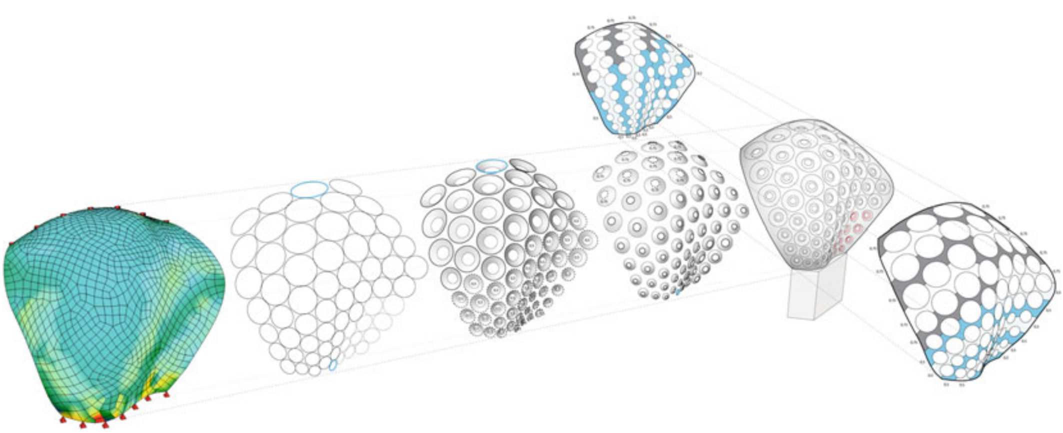

Fig. 12 Analysing the structural performance of a target surface informs the composition of the structure, which then gets optimized by either increasing the static height of the sandwich or the material density in the zones where it is needed the most

Fig. 13 The full-scale mock-up was built of PET-G plates with a thickness of only 0.5 and 0.75 mm

Conclusion

The evolution of bending-active plate structures and the associated form-finding and analysis techniques demonstrate the significant advancements that have occurred since Buckminster Fuller's first plydomes. The increasing availability of computing power and advancement of simulation tools have made it much easier to understand the complex interdependencies of bending-active structural systems as well as to master them for new designs. The integration of both geometric and material constraints from the start of the design process is a powerful approach that renders great potential for many applications. The case studies that are described in this paper indicate that the possible design space for bending-active plate structures is rich and offers a plethora of beautiful, efficient, and lightweight designs.

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