Bending-Active Plates

Form-Finding and Form-Conversion

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ABSTRACT

With this paper, the authors aim to contribute to the discourse on bending-active structures by highlighting two different design methods, form-finding and form-conversion. The authors compare the two methods through close analysis of bending-active plate structures, discussing their advantages and disadvantages based on three built case studies. This paper introduces the core ideas behind bending-active structures, a rather new structural system that makes targeted use of large elastic deformations to generate and stabilize complex geometrical forms based on initially planar elements. Previous research has focused mainly on form-finding. As a bottom-up approach, it begins with flat plates and recreates the bending and coupling process digitally to gradually determine the final shape. Form-conversion, conversely, begins with a predefined shape that is then discretized by strategic surface tiling and informed mesh subdivision, and which in turn considers the geometrical and structural constraints given by the plates. The three built case studies exemplify how these methods integrate into the design process. The first case study applies physical and digital form-finding techniques to build a chaise lounge. The latter two convert a desired shape into wide-spanning constructions that either weave multiple strips together or connect distant layers with each other, providing additional rigidity. The presented case studies successfully prove the effectiveness of form-finding and form-conversion methods and render a newly emerging design space for the planning, fabrication, and construction of bending-active structures.

1 Berkeley Weave installed at the courtyard of UC Berkeley's College of Environmental Design (CED).

INTRODUCTION

In recent years, the architecture community has witnessed an increased availability and constant improvement of computational tools that enable not only advanced geometrical modeling, but also the integration of real-time physics-based simulations into the design process in common CAD environments. Programs like Kangaroo Physics or SOFiSTiK are used, for example, to rapidly form-find and interact with particle systems or accurately analyze structures on the bases of Finite Element Methods (Piker 2013; Lienhard et al. 2011). With the help of these programs, one can describe and evaluate the mechanical behavior and structural capacity of a model under simultaneous consideration of external forces and internal material stresses.

2 Buckminster Fuller's 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.

3 ICD/ITKE Research Pavilion 2010 by the University of Stuttgart spans 10 m and consists of 80 birch plywood strips with a thickness of 6.4 mm.

With the rise of these tools, architects and engineers are becoming more and more interested in structural systems whose forms and load states cannot easily be predicted, but instead result from a delicate balance between geometry, interacting forces, and material properties. It is here, in particular, where physics-based simulations that provide real-time feedback can demonstrate their strength. Bending-active structures illustrate these interrelationships and as such are chosen in this paper as a detailed example (Figure 1).

This newly established structural system is characterized by the use of large elastic deformations of initially planar building materials to generate geometrically complex constructions (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. The underlying idea of exploiting a structure's flexibility in a controlled way is rather simple and extremely versatile. It can be used, for example, as a form-giving and self-stabilizing strategy in static structures or as compliant mechanism in kinetic structures (Lienhard 2014, Schleicher 2015).

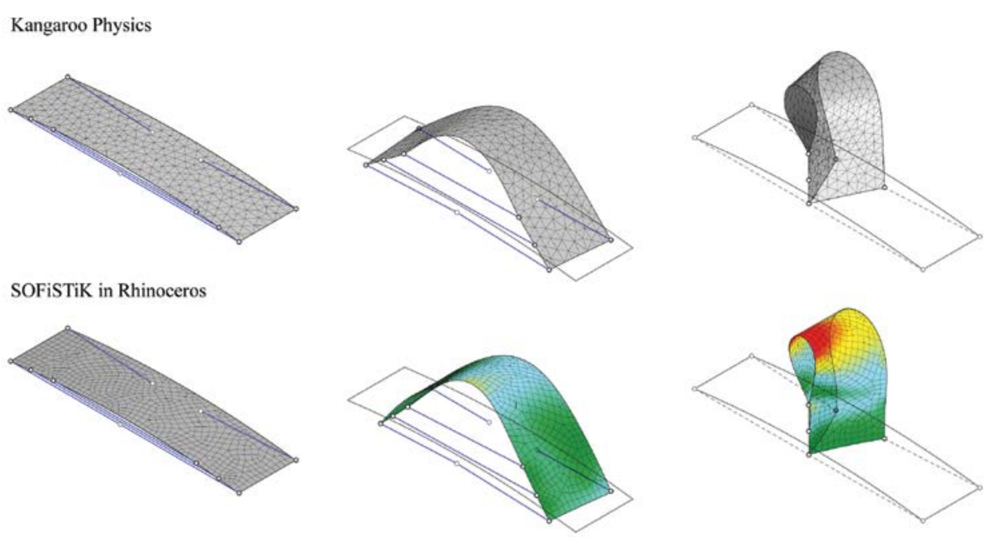
BENDING-ACTIVE PLATE STRUCTURES

Bending-active structures can be generally divided into two main categories, which relate to the geometrical dimensions of their fundamental components. One-dimensional (1D) systems can be built, for instance, by bending slender rods, while two-dimensional (2D) systems use thin plates as basic building blocks. While extensive knowledge and experience exists for 1D systems, with elastic gridshells as most prominent application, plate-dominant structures have not received much attention yet and are considered more difficult to design. One reason is certainly that plates have a limited formability, since they bend mainly along the axis of weakest inertia and thus cannot easily be forced into complicated geometries. However, what makes this subset of bending-active structures particularly interesting from a mathematical point of view is the fact that plates have a clear scale separation. They are typically very large in one dimension and progressively smaller in the other two. Their length is specified in meters, their width in centimeters, and their height only in millimeters. Having hierarchical geometrical features facilitates the further design process of bending-active plate structures and makes it easier to assess the structural behavior and accurately anticipate their deformed geometry with digital simulations.

Prominent examples for bending-active plate structures are Buckminster Fuller's plydomes and the ICD/ITKE Research Pavilion 2010 (Figures 2 and 3). While the first example follows a rational approach in which the shape of a sphere is approximated with a regular tiling of identical plates (Fuller 1959), the second example takes advantage of computational mass customization and joins 500 individual parts together (Fleischmann et al. 2012).

FORM-FINDING AND FORM-CONVERSION

A previous study identified three main design strategies for bending-active structures: a behavior-based, geometry-based, and integrative approach (Lienhard et al. 2013). According to this study, the first category refers to the traditional approach by skilled craftsmen who bend building materials intuitively on the construction site. The other two categories describe a more scientific approach, in which hands-on experiments and analytical tests were conducted beforehand and informed the further design and construction process. While the geometry-based approach relates to the idea of forcing an object to match a specific target geometry without further consideration of material properties, the integrative approach takes exactly these limiting factors into account when exploring a reachable design space. In order to best contribute to the above-mentioned classification of bending-active structures, it is the aim of this paper to further elaborate emerging design trends in the integrative approach by having a closer look at the techniques of form-finding and form-conversion.



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4 The form-finding approach starts from a flat sheet and uses contracting elastic cables elements to generate the final bent shape. Simulations in Kangaroo Physics allow for quick and interactive models while the software SOFiSTiK enables precise shape and stress analysis based on Finite Element Methods. (Schleicher et al. 2015).

Bottom-Up Design Using Form-Finding

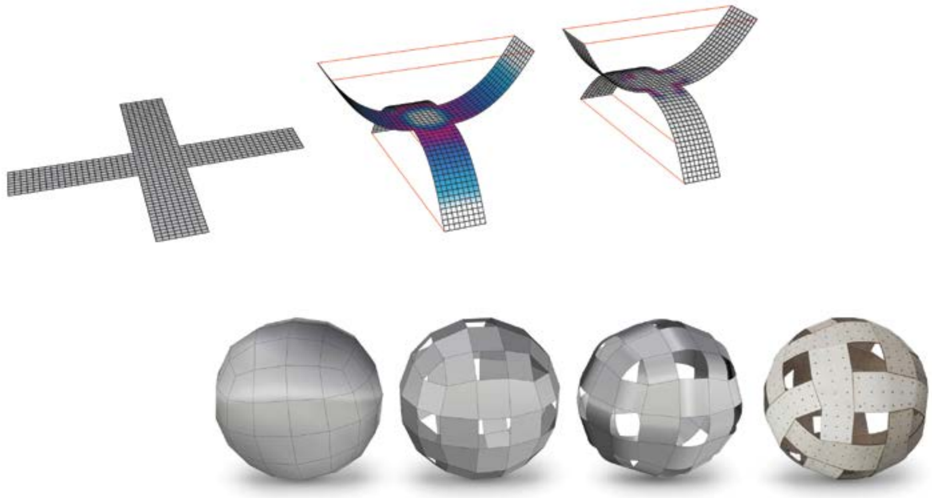
The term form-finding is best known for its role in the design of membranes and shell structures and refers to the concept of using physical models and numerical simulations to find an optimal geometry of a structure in static equilibrium with a design loading (Adriaenssens et al. 2014). From the 1950s onwards, architects and engineers focused on form-finding strategies that both incorporated materials and forces while enabling a systematic exploration of lightweight constructions. They became an essential part in the work of people like Buckminster Fuller, Félix Candela, Heinz Isler, and Frei Otto (Chilton 2000; Otto 2005). While these early pioneers implemented form-finding strategies to design shells and membranes determined by the shape of hanging chains and cloth, these techniques can also be applied for bending structures.

In the context of bending-active plate structures and digital simulation, form-finding is often used for a bottom-up design approach. It starts with planar sheets or strips to create the bending and coupling process in the final shape (Lienhard, Schleicher, and Knipper 2011; Fleischmann et al. 2012). By using spring-based simulations in Kangaroo Physics or finite element methods in SOFiSTiK, one can not only determine the resulting geometry of the deformed structure but also visualize the evolution of stresses within the material while the system is deforming (Figure 4) (Schleicher et al. 2015). Based on this information, one can cautiously bend a component, for instance by following an ultra-elastic cable approach until a permissible stress state is reached (Lienhard et al. 2014). The final shape and caused stresses are often unknown at the beginning, especially when multiple parts are bent and fastened together, which is a considerable drawback. A designer with a certain aim in mind would therefore have to conduct multiple simulations with gradually changing parameters to move closer to the design objective.

Top-Down Design Using Form-Conversion

In comparison to the previous method, form-conversion pursues a different approach when integrating geometrical and material considerations into the design of bending-active plate structures. Here, the process begins with a predefined target surface or mesh, which is then discretized and further subdivided into smaller bent tiles based on the flexibility of the used plates. The main restriction in this regard is the knowledge concerning the plates' material formability. Here, it is particularly important to know that for strips and plate-like elements, the basic shapes that can be achieved by pure bending without stretching are conical and cylindrical surfaces. These shapes are also referred to as single-curved or developable surfaces. Attempting to bend a sheet of material in two directions simultaneously either results in irreversible, plastic deformations or ultimate material failure. Thus, to expand the range of achievable shapes, it is necessary to develop other methods for the induction of Gaussian curvature into the system.

To overcome the limitations related to Gaussian curvature, multidirectional bending can be induced by strategically removing material and freeing the plates from the stiffening constraint of their surroundings. This principle is illustrated in Figure 5 and a similar approach was presented by Xing et al. (2011). Here, a continuous rectangular plate is reduced to two orthogonal strips. Once again, the strips are bent using the ultra-elastic cable approach of Lienhard et al. (2014). The bending stiffness of the plate, depending proportionally on its width, results in a radical increase of stiffness in the connecting area between the strips.



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5 The form-conversion approach is informed by the mechanical characteristics of a bent material and applies these principles to the subdivision process of a given target geometry. The upper row shows the multidirectional bending of a cross-like strip based on contracting elastic cables. The center image indicates the distribution of von Mises stress. The image on the right shows the Gaussian curvature. The bottom row uses these limiting factors for a form-conversion of a target mesh into an assembly of bent components.

As a result, the connecting area remains almost planar and the perpendicular bending axis remains unaffected by the induced curvature. In this way, it becomes possible to bend the strips around multiple axes, spanning different directions but still maintaining the material continuity of a single element. The center image of the cross-like strips in Figure 5 depicts the resulting von Mises stresses and clearly displays an area of unstressed material at the intersection between the two strips, which supports the previous arguments. A local stress concentration appears at the junction of the strips due to the sharp connecting angle as well as the inevitable geometric stiffening in that area.

The result of multidirectional bending can be compared with an analysis of Gaussian curvature on the right. From the plot, it is clear that the discrete Gaussian curvature of the deformed mesh is zero everywhere apart from a small, localized area at the intersection of the two branches. This confirms the assumption that, for inextensible materials, most developable surfaces (or slight deviation thereof) are achievable. Based on this approach, other arbitrary freeform surfaces can be converted, following the logic of strategic material removing and defined zones of local bending and planarity, as demonstrated in the lower images of Figure 5.

CASE STUDIES

To further illustrate the design potentials of a form-finding and form-conversion approach, the following section will have a closer look at three built case studies. While the first case study takes advantage of a bottom-up, form-finding technique to design a load-bearing chaise lounge, the latter two demonstrate the form-conversion of pre-defined shapes into wide-spanning constructions that gain rigidity by either weaving multiple strips together or connecting distant layers with each other.

Bending-Active Chaise Lounge

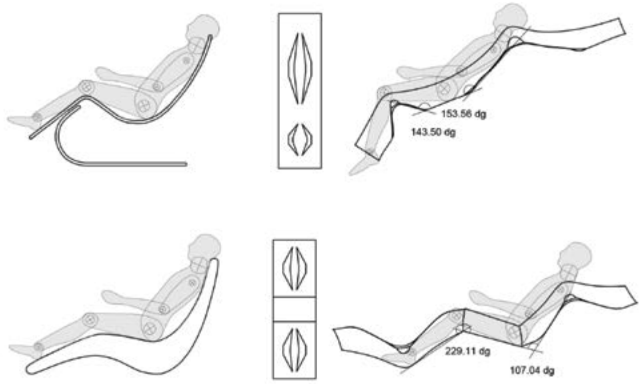
The first case study represents the previously mentioned form-finding process and demonstrates its design possibilities in the context of a furniture-scale object. The goal of this bending-active plate structure is to meet the highest structural demands yet only use a minimum amount of material. The application chosen to address this challenge in built form was a chaise lounge for one person.

In this project, bending is primarily induced by strategically removing material from the center of a thin sheet and then pinching its naked edges together and fastening the deformed shape with rivets. This technique has multiple benefits: generating intricate forms out of a single planar surface and achieving three-dimensional shapes that perform structurally in the bent state. The general design of the chaise lounge followed a gradual form-finding approach that comprised a series of physical models and digital simulations. In a first step, the geometry of different reference chairs and the relationship with the human body was studied and a group of target angles were identified that allow for a comfortable seating position (Figure 6). Based on this information, quick sketch models were built out of paper to gain a better understanding of the interdependencies between the cutting pattern and the angles of the deformed structure after the pinching.

The second step was to turn these cutting patterns into digital models. This was done in Grasshopper and the pinching simulated in Kangaroo Physics. At this point, the main advantage of using this type of spring-based simulation was the possibility for real-time feedback and user-interactivity to further modify the cutting pattern and improve the design (Figure 7). Furthermore, tracking the curvature of the mesh and identifying minimal bending radii allowed us to draw first conclusions if this form could be built out of a specific target material.

The following third step provided much more accurate results regarding the materialization of the chaise lounge. Here, SOFiSTiK was used to generate finite element models with defined material characteristics (Figure 8). All surfaces were given the material properties of high-density polyethylene (HDPE) with a Young's modulus of 1200 N/mm^2 and a thickness of 1.6 mm or 3.2 mm for a single or double layer. The model was then deformed using the ultra-elastic cable approach. Consulting this slightly more time-consuming method at this stage of the design process had multiple benefits. It allowed us to calculate the exact geometry of the highly deformed structure and assess the stresses within. Thus, this simulation is a much more complete description of the mechanical behavior and structural capacity of the bending-active system. Furthermore, the feedback on the structure's complex equilibrium state also allowed localizing potentially dangerous stress concentrations. And last but not least, having done the simulation in typical engineering software also made it possible to further analyze the chair's structural performance once the weight of a human body was added.

As a proof of concept, the chaise lounge was built both as a series of small-scale models as well as a full-scale chaise lounge with the dimensions of 2.44 m x 1.22 m x 1.6 mm (Figures 9–10). The construction material was HDPE, the patterns for the different sheets were cut on a Zünd blade cutter, and the pieces were connected together with steel rivets. Riveting, and in particular blind riveting, was used in this project both to permanently pinch each surface as well as to connect multiple plates with each other. Since rivets can only transmit tension and shear forces, their exact position needed to be determined carefully. In this regard, the iterative from-finding over multiple simulations



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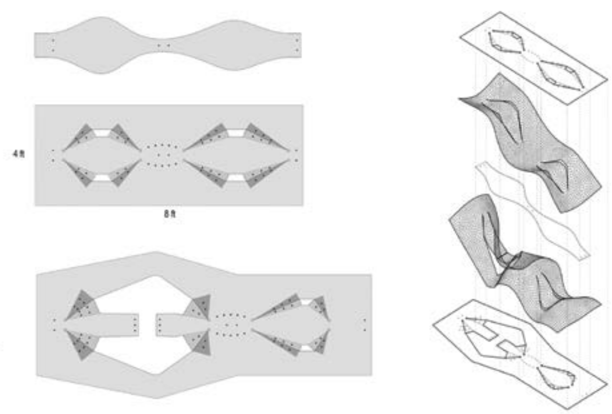

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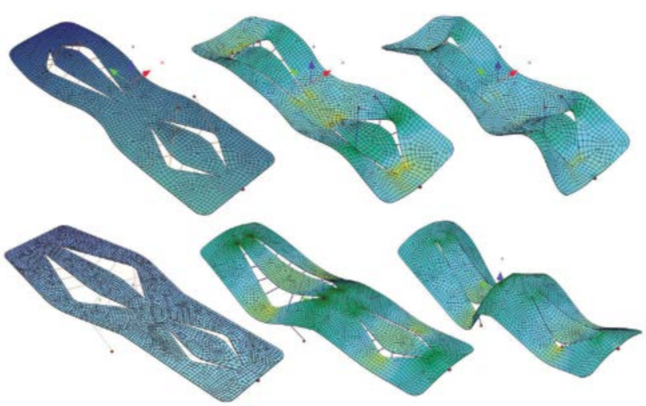

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6 Different reference chairs were analyzed for their seating position and the angles therein were recreated by pinching flat sheets into a deformed shape.

7 Digital simulations in Kangaroo Physics were used to quickly test different cutting patterns and form-find the desired geometrical form.

8 Structural validation of the form-found shape based on FEM simulations and a thorough analysis of the appearing minimal bending radii.

9 A series of paper and plastic sketch models were used to gradually approach the final shape and ascertain the required cutting pattern.

10 Full-scale prototype of the bending chaise lounge is built out of 1.6 mm thin HDPE plastic and is able to carry the weight of a person.

11 Berkeley Weave installation spans over 4 m and is built out of 480 individual plywood strips with a thickness of only 3 mm.

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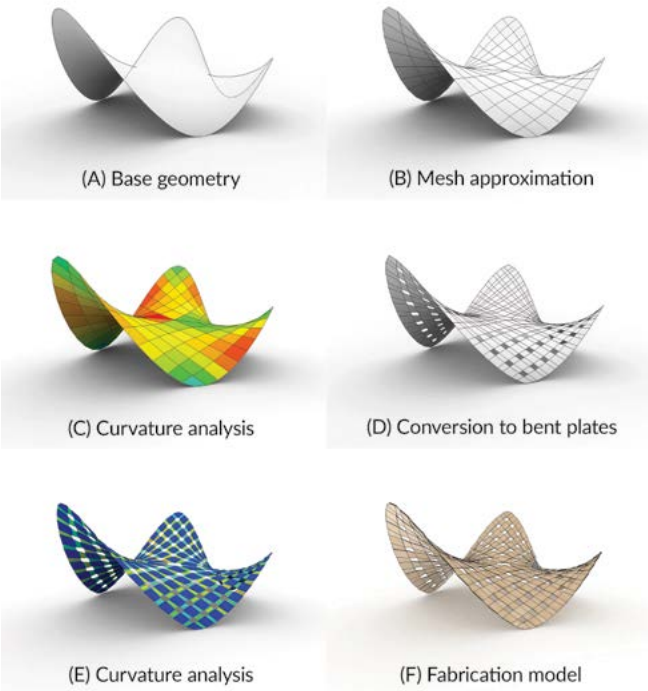
played an important role. It provided crucial information about the precise geometry of the deformed plates as well as the exact position of the rivet holes, which was needed to guarantee the alignment of all layers. As far as the actual assembly of the chaise lounge is concerned, the bending of the plastic was rather easy and could be done manually. In fact, it was surprising how rigid the structure became once all pieces were fastened together and the stored elastic energy began to pre-stress the structure. The final chaise lounge was capable of carrying the weight of a person, of course under some deflections but within permitted tolerances (Figure 10).

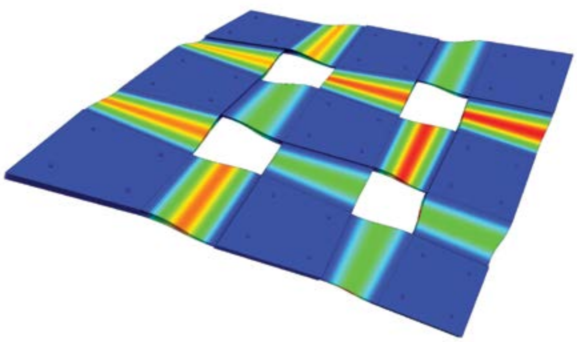
Berkeley Weave

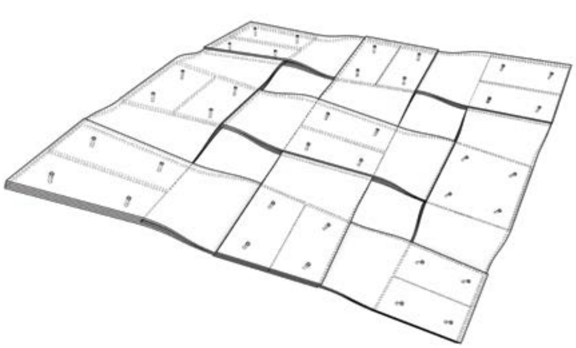
In contrast to the previous example, which uses only a small number of parts, designing bending-active plate structures out of multiple components is very challenging and thus requires a different approach. For this reason, the second case study applies a different method and aims to demonstrate the design potential of form-conversion (Figure 11). It investigates an integrative approach that considers not only bending but also torsion of slender strips. The saddle-shaped design of the Berkeley Weave is based on a modified Enneper surface (Figure 12a). This particular form was chosen because it has a challenging anticlastic geometry with locally high curvature. The subsequent conversion process into a bending-active plate structure followed several steps. The first was to approximate and discretize the surface with a quad mesh (Figure 12b). A curvature analysis of the resulting mesh reveals that its individual quads are not planar but spatially curved (Figure 12c). The planarity of the quads, however, will be an important precondition in the later assembly process. In a second step, the mesh was transformed into a four-layered weave pattern with composed strips that feature pre-drilled holes. Here, each quad was turned into a crossing of two strips in one direction with two other strips at a 90-degree angle. The resulting interwoven mesh was then optimized for planarization. However, only the regions where strips overlapped were made planar, while the quads between the intersections remained curved (Figure 12d). A second curvature analysis illustrates the procedure well and shows zero curvature at the intersections of the strips (blue areas) while the connecting arms are both bent and twisted (Figure 12e). Specific routines in the form-conversion process guaranteed that the bent zones stayed within the permissible bending radii. In the last step, this converted shape was used to generate a fabrication model that featured all the connection details and strip subdivisions (Figure 12f).

A closer look at the most extremely curved region illustrates the complexity related to this last step (Figure 13). To allow for a proper connection, bolts were only placed in the planar regions between intersecting strips. Since the strips are composed out of smaller segments, it was also important to control their position in the four-layered weave and the sequence of layers. A pattern was created which guaranteed that strip segments only ended in layer two and three and are clamped by continuous strips in layer one and four. A positive side effect of this weaving strategy is that the gaps between segments are never visible and the strips appear to be made out of one piece. The drawback, however, is that each segment has a unique length and requires individual positions for the screw holes (Figure 14).

To demonstrate proof of concept for this design approach, this case study was built in the dimensions of 4 m x 3.5 m x 1.8 m (Figure 11). The structure is assembled out of 480 geometrically different plywood strips that were fastened together with 400 bolts. The material used is 3.0 mm thick birch plywood with a Young's modulus of $E_{m\parallel} = 16471$ N/mm^2 and $E_{m\perp} = 1029$ N/mm^2. Dimensions and material specifications were employed for a finite element analysis using the software SOFiSTiK. Under consideration of self-weight and stored elastic energy, the minimal bending radii are no smaller than 0.25 m







12 Form-conversion process and analysis of the Berkeley Weave.

13 Analysis of Gaussian curvature in the area with the highest deformation.

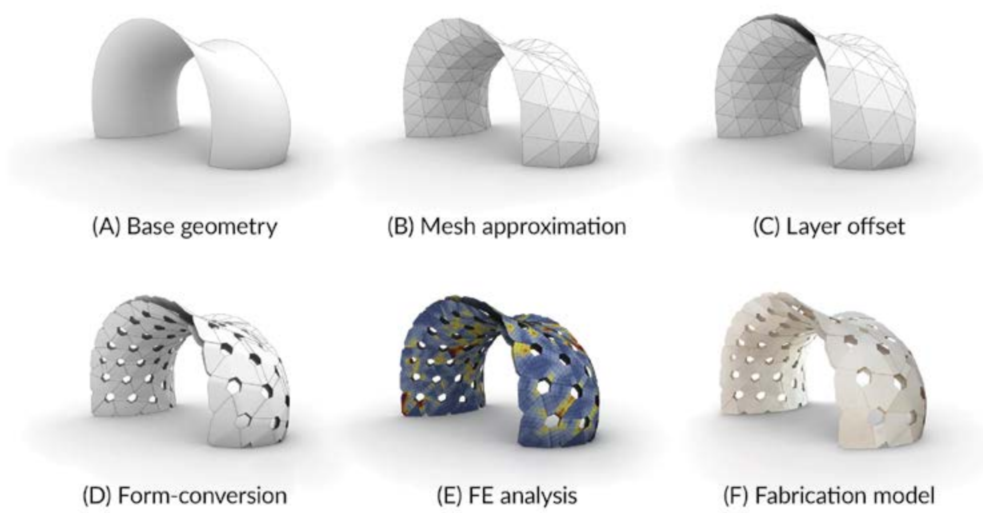
14 Schematic drawing of the technical details in the four-layered weave.

and the resulting stress peaks are still below 60% of permissible material utilization.

Bend9

The third case study showcases another take on form-conversion for bending-active plate structures that consists of many components. This project is a multi-layered arch that spans over 5.2 m and has a height of 3.5 m. It was built to prove the technical feasibility of using bending-active plates for larger load-bearing structures. In comparison to the previous case study, this project implements a different tiling pattern and explores the possibility of significantly increasing a shape's rigidity by cross-connecting distant layers with each other. To fully exploit the large deformations that plywood allows for, the thickness of the sheets had to be reduced to the minimum, leading once again to the radical choice of employing 3.0 mm birch plywood. Since the resulting sheets are very flexible, additional stiffness needed to be gained by giving the global shell a peculiar geometry, which seamlessly transitions from an area of positive curvature (sphere-like) to one of negative curvature (saddle-like) (Figure 15a). This pronounced double-curvature provides additional stiffness and helps avoid undesirable deformation of the structure. Despite the considerable strength achieved by the shape alone, the choice of using extremely thin sheets of plywood at that scale asked for additional reinforcement to provide further load resistance. These needs were met by a double-layered structure with two cross-connected shells.

As in the previous example, the first step of the process was to convert the base geometry into a mesh pattern (Figure 15b). In the next step, a preliminary analysis of the structure was conducted and informed the offsetting of the mesh to create a second layer. As the distance between the two layers varies to reflect the bending moment calculated from the preliminary analysis, the offset of the surfaces changes along the span of the arch (Figure 15c). The offset reflects the stress state in the individual layers, and the distance between them increases in the critical areas to increment the global resistance of the system. The following form-conversion process was once again driven by material constraints and previously determined permissible stress limits with respect to bending and torsion. The resulting tiling logic that was used for both layers affected the size of the members and guaranteed that each component could be bent into the specific shape required to construct the whole surface. More precisely, this is achieved by strategically placing voids into target positions of the master geometry, ensuring that the bending process can take place without prejudice for the individual components (Figure 15d). Although initially flat, each element undergoes multi-directional bending and gets locked into position once it is fastened to its neighbors. The flexible 3.0



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15 The form-conversion process of Bend9 pavilion started from a base geometry (A) and approximated this shape with a mesh (B). Based on a first structural analysis, the mesh was offset and turned into a double layer. This structure was then converted into an assembly of bent plates (D). After another finite element analysis (E), a fabrication model was generated (F).

16 Detail of the assembled structure shows the layering of different components and the strategically placed voids to prevent conflicts between the bent parts.

17 Custom wood profiles were used to cross-connect the two layers together and thus increase the structural capacity of the pavilion significantly.

mm plywood elements achieve consistent stiffness when joint together, as the pavilion, although a discrete version of the initial shape, still retains substantial shell stiffness. This was validated in another finite element analysis that considered both self-weight as well as undesirable loading scenarios (Figure 15e).

Finally, after fabrication, the structure was assembled on site. The built structure employs 196 elements unique in shape and geometry (Figure 16). 76 square wood profiles of 4 cm x 4 cm were used to connect the two plywood skins (Figure 17). Due to the varying distance between the layers, the connectors had a total amount of 156 exclusive compound miters. The whole structure weighs only 160 kg, a characteristic that also highlights the efficiency of the system and its potential for lightweight construction. The smooth curvature transition and the overall complexity of the shape clearly emphasize the potential of the construction logic. Furthermore, the implemented form-conversion process can be applied to any kind of double-curved freeform surface, not only the one built at UC Berkeley's campus (Figure 18).

CONCLUSION

In summary, it can be concluded that the three case studies clearly illustrate the feasibility of form-finding and form-conversion techniques for the design of bending-active plate structures. All three examples showcase an integrative approach that is directly informed by the mechanical properties of the thin plastic and plywood sheets, which were employed in the different projects. Their overall geometry is therefore the result of an accurate negotiation between the mechanical limits of the materials and

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18 View of the Bend9 structure assembled out of 3 mm thin birch plywood in the courtyard at UC Berkeley's College of Environmental Design (CED).

their deformation capabilities. The very nature of all three case studies required a tight integration of design, simulation, and assessment of fabrication and assembly constraints.

Due to its small number of parts, the bending chaise lounge was a good case study to demonstrate the potential of design processes based on iterative form-finding. Depending on the simulation software used, this method can be very quick and interactive or particularly accurate and reliable regarding its results. This precision, however, comes at the expense of simulation speed. Therefore, form-finding meets its natural boundaries when the number of parts exceeds a certain limit.

The second and third case studies aimed to tackle this challenge by presenting form-conversion as an alternative design approach for bending-active plate structures that consist of many parts. Furthermore, the Berkeley Weave and the Bend9 pavilion exemplify the capacity of bending-active plate structures to be employed as larger scale, space-framing architectural interventions. For future research, the presented case studies and the underlying design routines of form-finding and form-conversion will serve as first prototypes for the exploration of more complex surface-like shell structures that derive their shape through elastic bending.

ACKNOWLEDGEMENTS

The authors would like to thank the following student team for their amazing work on the bending chaise lounge and their indirect contribution to this paper: Cindy Hartono, Fei Du, Shima Sahebnassagh, Eleanna Panagoulia as well as their additional supervisors Prof. Kyle Steinfeld, Prof. Jonathan Bachrach, and Luis Jaggy. For the Berkeley Weave installation, the authors would particularly like to thank Sean Ostro, Andrei Nejur, and Rex Crabb for their support. Finally, the Bend9 pavilion would not have been possible without the kind support of Autodesk's Pier 9 and its entire staff.

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IMAGE CREDITS

Figure 2: Marks, 1973
Figure 3: Schleicher, 2010
Figure 4: Schleicher et al. 2015
Figures 6–9: Hartono, Du, Sahebnassagh, Panagoulia, 2015
All other photography: Schleicher and La Magna, 2016

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