DESIGN, ANALYSIS AND ROBOTIC FABRICATION OF A BENDING-ACTIVE SHELL STRUCTURE WITH THIN SHEETS BASED ON CURVED-CREASE-FOLDING TECHNIQUE

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Abstract. This paper shows a design and building application of an innovative structure concept which is developed by the authors. The long-span shell structure (8m*10m*2.5m) built with 1.5mm thin aluminum sheets demonstrates the possibility to apply bending-active structures with flexible thin sheet material in shell structures to enhance the global and local stiffness. The structure is mainly originated from the curved-crease-folding technique which enhances the structural stiffness by introducing curvature to the surfaces. The Y-shape structural elements define the basic geometrical rules and find its global double-curved geometry via the folding of the three lateral ribs. The full-scale prototype and its design and fabrication techniques show a design framework of the structure from its form-finding, surface optimization, robotic simulated fabrication to the final full-scale assembly. As a pioneer pavilion in a research workshop, students' design with diverse forms also show the widely possible application of this structural concept.

Keywords. Shell structure; thin aluminum sheets; bending-active; robotic creased-folding.

1. Introduction

Active-bending presented with its developments in recent years an inspiring approach to generate lightweight structural typologies which obtain their curved geometry as well as the high structural stiffness by means of elastic bending from initially planar load-bearing elements (Lienhard and Knippers 2014). The pre-stressing effect during the bending process enables materially efficient system especially for the building materials which have high load-bearing capacity but with relatively low stiffness (Fleischmann et al. 2012). Referring to a non-linear physical approach rather than a specific structural typology, the design of bending-active structures usually requires a complex matching of materials' property, geometrical features as well as the forming and fabrication techniques (Liuti et al. 2018).

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Being a typical art form in the traditional human craftsmanship, curved-crease-folding shows a well combination and intuitive application of the advanced forming technique with the flexible materials as well as the hidden structural principles of active-bending. It is not until the historic work of Huffman and Ron Resch in the 1970s that the geometry of curved-crease-folding went into the field of architectural design and computational design with its energetic curved geometry and great potential to create a simply fabricatable curved shell surface (Demaine et al. 2011). Recent researches on the curved-crease-folding focus mainly on the geometric rules and the digital simulation methods (Kilian et al. 2008, Bhooshan 2016) as well as the structural' behavior of the Origami structure (Robeller et al. 2014). However, a design framework of the structure system and corresponding design tools for architects as designers still lack to invoke the emerge of innovative bending-active shells based on the curved-crease-folding technique.

Figure 1. A Full-scale Long-span Pavilion built with the structure concept .

It is since 2012 that the authors have started the researches on applications of thin sheet materials on shell structures. Researches have been done in various designs to tests the possibilities such as the grid-shell system, cellular hybrid system to develop efficient shell structure concepts for certain materials. With the development of computational fabrication techniques and the inspiring researches on the curved-crease-folding geometry, it was in a design workshop in Nanjing University, China that a structural concept and its design system was established and tested with a long-span shell structure pavilion with aluminum alloy sheets only 1.5mm thick as structure material. In this paper, detailed researches of such concept and an experimental application of the full-scale pavilion (Figure 1) are presented.

2. Structural Concept and Geometric Optimization

In the preliminary researches on the materials and the structural behavior of shell and plate structures, it is understood that the flexible property of the thin sheets requires both global and local special structure concept and solutions such as the form-finding and local stiffening technique to ensure the stability of the thin cross section. It is well known in a common knowledge as well as the structural researches that bending and folding (especially into doubly-curvatures) will enhance the stiffness of the thin sheets (Siegel 1960, Pini et al. 2016), hence to create the appropriate double curvature as well as stiffening the whole structure will be the initial goals of the design framework. Based on the pre-researches on the geometries of curved-crease-folding structures and the developable surfaces (Brancart et al. 2015, Bhooshan 2016, Kilian et al. 2008), a structured system based on the combination of Y-shape curved-folded structural elements (Figure 2) is generated to be applied in the design system.

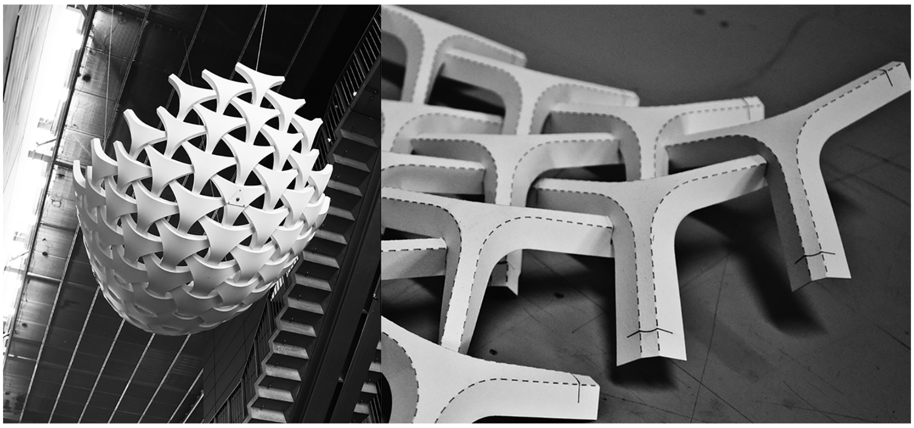

Figure 2. Pre-researches on the curved-crease-folded structural elements and the basic Y-shaped structural elements.

2.1. GEOMETRIC ABSTRACTION AND GLOBAL FORM FINDING

Compared to the traditional curved-folded origami geometry, the first consideration in the design of the structural system presented in this paper starts with the determination of the global equilibrium state of all the structural elements. As shown in Figure3-a, in the global geometric abstraction of the system, all the Y-shaped elements are simply understood as the combinations of a 3-line system, therefore the whole structure can be simplified as a funicular 3-valence mesh system. As bending behavior is dangerous to the flexible thin sheet materials, a pure axial internal force field is welcomed by the structure system. In this way, a basic principle of the design of the structure concept is an initial form-finding technique such as the Force-Density Method or the Dynamic-Relaxation Method (Figure 3-b). This defines the fundamental global behavior of the whole structure.

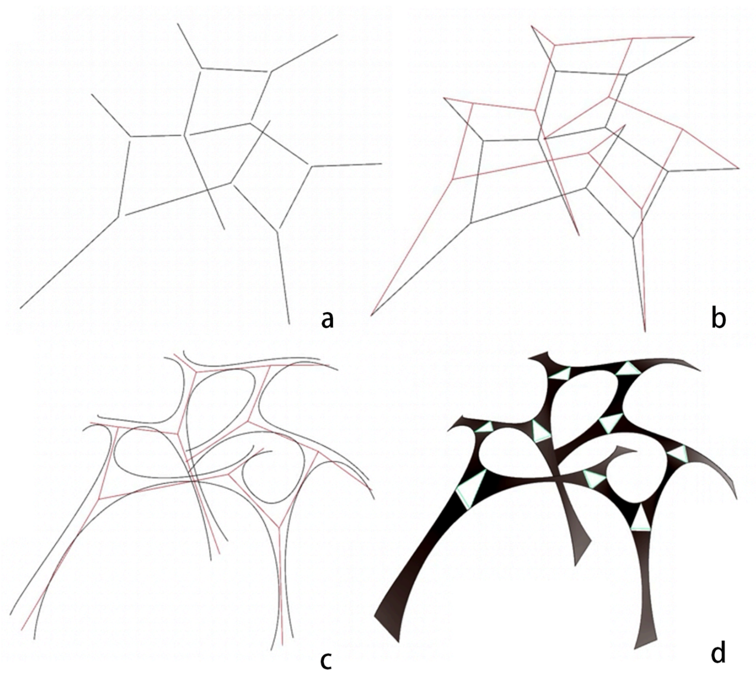

Figure 3. Form-finding and the geometric operation in the design of the structural system (a, structure is understood as a 3-valence mesh system; b, form-finding technique is applied on the system to define the global behavior; c, spatial curves are generated based on the funicular system; d, developable surfaces are generated with triangles at the joint points).

Because in the real structure the geometry will be consist of a covering surface and three lateral supporting ribs, it is trivial to discover that the local curved geometry of the covering surface is correlated with the rotating angle of the bendable supporting ribs. It is assumed that all the smooth spatial curvature could be derived from the local curved-bending, the global design of the funicular system can be developed with a further process to generate 3 continuous spatial curved by simply offsetting the 3 valences of the mesh and interpolating a curve along the discontinuous vertexes (Figure 3-c). The 3-valence property of the initial mesh will provide an ideal characteristic of the curved surface that all the 3-valence curved surfaces can be divided into a combination of 3 lofted developable surfaces (defined by 2 adjacent spatial curves) and a planar triangle in between (Figure 3-d). This ensures the property of the structural system that all the surfaces are developable and that they can all be unrolled into the planar continuous patterns.

2.2. CREASE-FOLDING AND THE STRUCTURAL CONSIDERATION

With the planar development of the 3d-curved surfaces, a basic pattern for the bending-active system can be derived by offsetting the boundaries of the unrolled surface (Figure 4-a). Through the crease-folding following the boundary curve, the whole structure will be bent up and the stiffness will be enhanced by the activated curvature in the geometry (Figure 4-b). The curvature of the structural elements can be controlled by the rotating angles of the lateral supporting ribs, and hence the local form as well as the stiffness can be adjusted by controlling the magnitude of the bending forces.

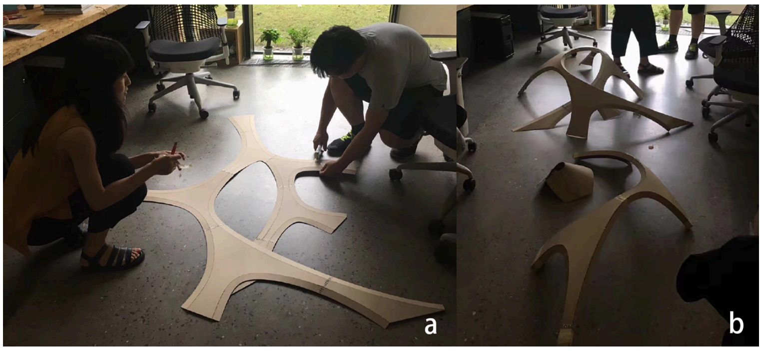

Figure 4. Tests with the unrolled developable surfaces and the curved-crease-folding technique (a, creating supporting ribs by offsetting the planar boundaries; b, generate the spatial curved surfaces with curved-folding).

Although the structure is divided into the main covering surfaces and the lateral supporting ribs, the discrete structural elements in the form-finding process cannot be considered separately as independent parts. In the 3d-curved geometry, although the individual parts of the developable lofted surfaces are all considered to be single-curved, the general geometry shows a quasi-doubly-curved behavior due to the valences in the structure everywhere. Thanks to the preliminary form-finding of the global geometry, a relatively ideal geometry is ensured for the main covering surfaces. The internal stress, in this way, should flow along a pre-found and pre-defined path and this helps the structure to be efficient with the super thin cross section. However, for the long-span element in the structure system, if the structure is not secured by the lateral supporting ribs, a buckling behavior is easily to happen even there is only pure axial stresses in the surface. In this way, the lateral ribs in the creased-folding process, will not only play the role as the global actuator of the structural behavior, but also an important role as the main guarantee for the safety of the local elements against buckling. When a large bending moment is applied on the ribs, the whole structure will bend to a very large extent and it will also activate a greater stiffness as well as a larger back-bouncing force. In this way, if all the boundary conditions- including the supports and the free bent lateral ribs- are well fixed and constrained, the coupling of the covering surfaces and the ribs will together make the whole structure a well-stabilized system.

3. Simulation and Robotic Fabrication

The state-of-the-art simulation method of the curved-crease-folding methods were established firstly from the researches on the developable surfaces, and further developed in the recent years, and could be briefly categorized into 2 groups: the geometrical solution (the mapping method from the planar pattern to the 3d results) (Vergauwen et al. 2014) and the kinetic solution (the translation of controlling points from one state to another) (Lienhard and Knippers 2014, Epps and Verma 2013).

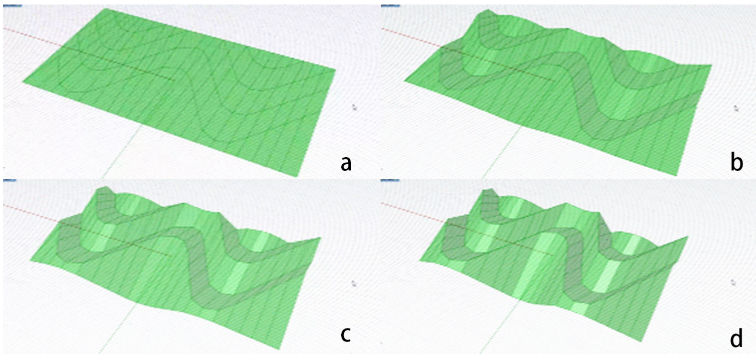

Figure 5. Simulation of the active-bending procedure based on the curved-crease-folding techniques.

The simulation of the active-bending procedure is necessary to find the final form of the built structure, because every small change of the bending angle will result in a slight different final form. A hybrid method based on the previous geometric research on the curved-folding(Kilian et al. 2008) (Epps and Verma 2013) is applied in Grasshopper®. A planar quad lateral (PQ) tessellation based discretization method is firstly applied onto the planar developed surface (sometimes the PQ parts are connected with smaller triangular facet in-between). In the next step, physical kinetic simulation tools such as Kangaroo is used to simulate the actuation behavior of the lateral bending. The active-bending behavior is hence calculated in such an iterative way (Figure 5).

To control the final geometry of the structure, a global bending simulation is made with the FEM analysis, using original boundary curves as guidelines for the final simulation. Angles of every part of the PQ mesh is exported to the output file as the guide for the final fabrication. In the final fabrication, as the bending angle varies everywhere, a robotic-aided bending method is developed to control the geometry accurately (Figure 6).

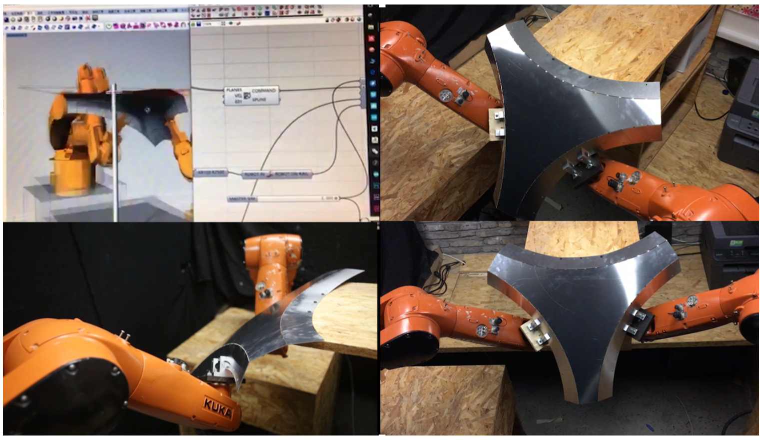

Figure 6. Robotic Fabrication of the Prototype element (2 bending robots and one fixed side).

4. Assembly and Structural Analysis

The final pavilion is divided into 19 elements which were all pre-fabricated by the robot-bending system and finally assembled in-place. The global geometry of the pavilion is defined through a form-finding technique of shell structure with a funicular system according to the above-mentioned design technique. Benefited from the accurate prefabrication, he final assembly process of the complicated and large shell pavilion demonstrates the high efficiency of the structural concept. The whole fabrication and building process of the large pavilion is finished by a workshop in only 3 hours with 15 students (Figure 7).

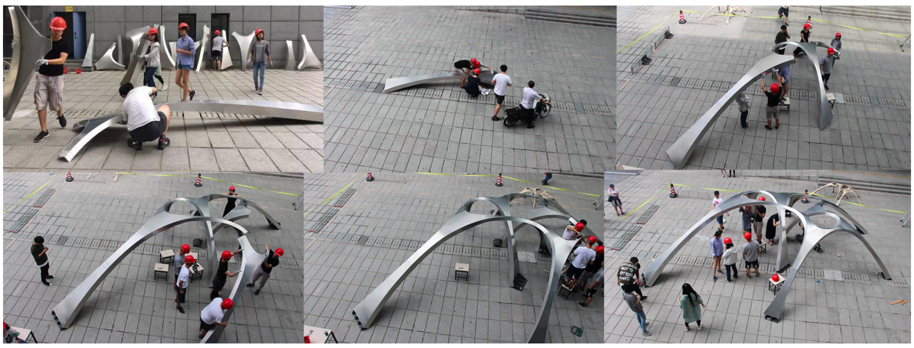

Figure 7. The fabrication and final assembly of the bending-active shell pavilion.

The high stiffness of the structural element itself helps the structure to support itself during the final assembly. Each element weighted only about several kilograms so that it is convenient for the student to carry and move the structural element into the right position. Human labor only needed to be added to help the structural element to hold its position and connecting the adjacent elements. Although the structure is built with only 1.5mm thick aluminum, it shows a great stiffness both individually and together as a whole. As screw holes were prefabricated with CNC laser cutter for the connections, the accuracy of the arrangement of adjacent elements can also be provided during the assembly process. Hence the building techniques of the proposed in this paper is also demonstrated to be feasible to be used in complicated shell designs.

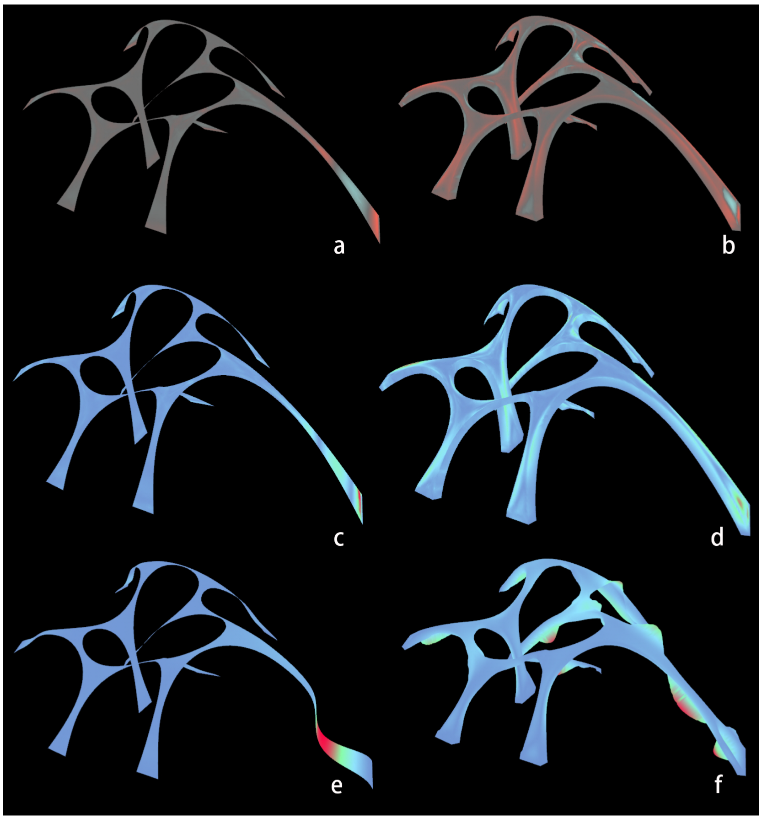

Figure 8. The Structural Analysis of the Designed Bending-active Pavilion (a,b: Principal Stresses; c,d: Bending Moments; e, f: Displacements).

A full structural analysis with the Finite Element Method is carried out with the Karamba Plugin in Grasshopper® with the comparison of different structural models (considering the lateral stiffening effect of the supporting ribs) (Figure 8). The connection between the covering surface and the lateral ribs were defined as rigid connection because of the construction details with the holes on the cutting lines. It can be obviously found in the results that although the structure was designed with a preliminary form-finding process, the main covering surfaces itself still showed a flexible property due to its ultra-thin cross-section. In contrast, the comparing model with the supporting lateral ribs, the structural behavior was largely improved. In Figure 8-a &b, the principal stresses in the structure were declined more than 5 times from the pure surface model to the coupled model (from 12.58MPa to 2.56MPa). In Figure 8-c &d, the most important bending moment reduced largely from 4.64Nm (pure surface) to 0.25Nm (with supporting ribs). And Figure 8-e &f also show the great reduction of the displacement of the whole structure with the help of the ribs (from maximum 32.08mm to 0.20mm).

5. Student Works based on the Structural Concept and the Design Tools

As a prototype for a students' workshop, it is also the aim of the pavilion's design that it could help to establish a widely applicable structural concept and a series of useful design tools to help the students to discover the potentials of the bending-active structures based on the curved-crease-folding. With the tools such as the form-finding algorithms, generators of developable surfaces and the bending simulator, students have finished inspiring structure design according to the similar workflow of the design of the prototype.

With the advanced computational design tools, students joined the development as well as the research of the structure concept in this paper. The complicated structural behavior could be visualized and analyzed in a direct and expressive way and the parameters also defined the clear logic behind the coupling relationship between the geometry and the physical behavior. With a series of families of designs, students established their own shape grammar based on the understanding of the structural concept and its performance.

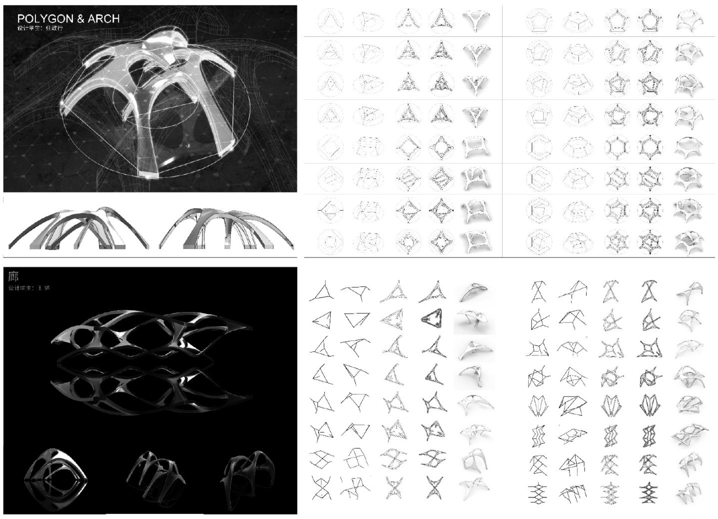

Figure 9. Students' Design Researches on the Bending-active Structures based on the Curved-crease-folding.

6. Conclusion and Future Researches

The successful design and building experiments of the shell structure, its robotic fabrication, full-scale assembly as well as the structural analysis demonstrated the feasibility to use super-thin materials in the long-span spatial structures. It also showed the validity that the active-bending provided a potential approach to discover more inspiring structural concept by considering both the material and their forming techniques. The research method of the generation process of this structural concept will lead a further detailed research on the digital simulation of the non-linear bending behavior in the curved-folding geometry, as well as a full-automated robotic fabrication.

Acknowledgement

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