BENDING-ACTIVE METAL PANEL DEFORMATION

Control through Computational Simulation and Pattern Development

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Abstract. This paper aims to complement the discourse of bending-active systems by exploring a related design strategy, form-approximation. The authors explore the said strategy through analysing bending-active plate systems and commenting on its advantages and disadvantages based on physical prototype experiments and a self-built case study. Previous research has revealed that form-finding and form-conversion have their unique characteristics respectively. The authors demonstrate a new strategy of modelling the Miura origami pattern into a representation of bending-active plates and to convert the desired shape into a pattern-sewed bending-active plate construction through linear regression. The physical prototypes and fabrication experiments demonstrate the effectiveness of the form-approximation method and present a newly emerging strategy for the design and fabrication of bending-active systems.

Keywords. Bending Active, Material System, Digital Fabrication, Computational Simulation, Miura Fold

1. Bending-Active System

Over the past decade, the architecture community has constantly utilised computational tools to realise complex modelling and has introduced various physics-based simulations in CAD environments to evaluate the external and internal behaviours of materials in structural systems. Bending-active system has therefore been widely discussed in the architecture community. “Bending-active systems can be generally divided into two main categories, which relate to the geometrical dimensions of their fundamental components (Schleicher and Magna, 2016, p. 262). ” The one-dimensional systems that are built by bending linear rods as components, and the two-dimensional systems that employ thin plates as panels.

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1.1. FORM-FINDING AND FORM-CONVERSION

Previous strategies on the bending-active system can be divided into form-finding and form-conversion. "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. (Fleischmann et al., 2012)." An example would be the Mannheim Multihalle by Frei Otto, with its multi-curved grid made of wooden slats. However, the results are often unpredictable and require extensive experimental trainings during the design phase. On the other hand, the focus of the form-conversion strategy is to use the differential method to disassemble complex geometry into developable surface units. "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 (Schleicher and Magna, 2016, p. 262)." An example would be the Bend 9 Pavilion, with "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 (Schleicher and Magna, 2016, p. 266)." Although this appears to be a more predictable design strategy, the two-dimensional units made using the form-conversion strategy usually come with uncontrollable edges in order to adapt to the three-dimensional form. This often leads to a considerable amount of material being wasted during the fabrication step.

2. Materials and Methods

In this research, aluminium has been selected as the target material, which has a high potential for use in bending-active systems (ratio of $\sigma m,Rk/E = 4.71$). "Adequate materials for bending-active structures offer a ratio of $\sigma m,Rk/E > 2.5$ (with σ m,Rk [MPa] and E [GPa]). For elastic kinetic systems, the additional requirements for fatigue control further limit the permissible permanent elastic stress (Lienhard, 2014, p. 36). To maintain the simulation accuracy, it is important that the occurrence of long-term permanent creep deformation is avoided. At this point, the visualised mean curvature is measured to better understand the deformation status.

To fully realise the bending performance of each layer of thickness of the aluminium plate, this research tests the deformation range of the aluminium plate to adjust the threshold of elasticity in the simulation program. This parameter is important for later design phases where they can be input into the computer model to establish a simulation of the elasticity of the aluminium. In sum, the result of the bending deformation testing reveals that the thinner plate meets the permanent creep deformation at higher curvature bending, which implies that the thinner aluminium plate has a wider quantity of bending ability, allowing more room for deformation. After comparing each thickness bent testing, the aluminium plate thickness of 0.2mm has been selected and the permanent creep deformation of the mean curvature value is at 0.0362.

Overall, the workflow consists of three main stages, beginning with the build-up of the origami representation, the conversion process, and, finally, the transfer of model analysis information from the three-dimensional simulated model back to the two-dimensional fabricated model (see figure 1)

To begin with, an origami model has been set up in a two-dimensional environment, using planar sheets to create the folded model and coupling it with the target shape. As the folded model is coupled with the target shape, the patterns of the folded model are then converted correspondingly to the various openings based on each folded angle of the pattern through the mathematical function library, thereby obtaining a simulated bending-active model. Here, the mesh interrelationship has been maintained as same as the initial plate mesh, so as to fabricate with planar sheets. The placement of the openings on the three-dimensional model are therefore directly relocated onto the planar mesh.

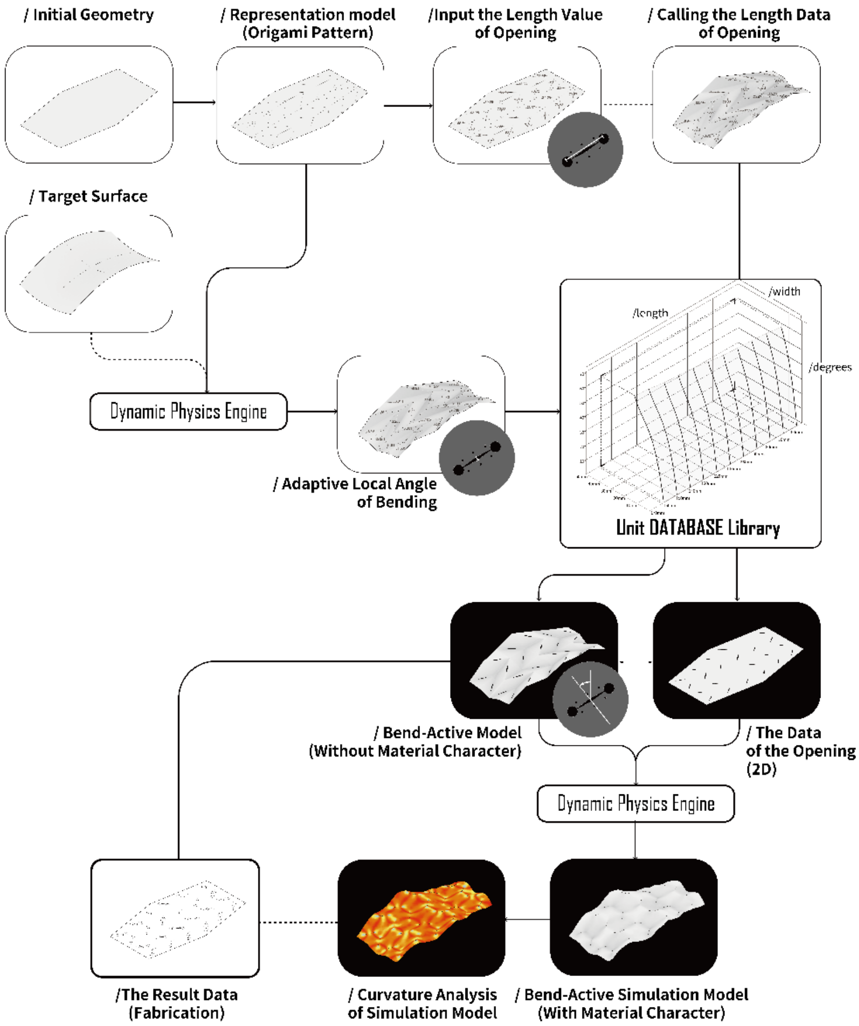

Figure 1. Workflow of pattern-based strategy in bending-active system

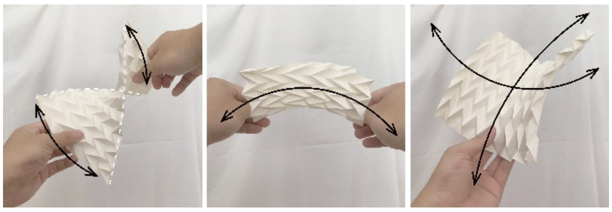

Figure 2. Characteristics of Miura folding

Figure 3. 3D scan process

2.1. FORM APPROXIMATION BASED ON AN ORIGAMI PATTERN

When it comes to pattern scales, this research discovers that, based on the pattern angle differences, the pattern of Miura fold satisfies the leading surface flow and performs particularly well with arches, twists, and saddles (see figure 2). At this point, the Miura fold has been introduced as the representation. When the representation approximates the target geometry, it shows the local angle of each pattern, and then the peak and valley angles are translated into opening values, making it easier to predict the bending deformation of the overall surface through the various bending differences caused by the opening values of the local patterns. Lastly, this research presents a series of typical surfaces in order to verify the result of the bending-active strategy and to see if the representation of Miura fold maintains the global surface characteristics (see figure 4). EinScan Pro+, a 3D scanning device with accurate tolerance under 0.3mm and the point gaps of points cloud under 0.4mm, has been employed to scan the real mock-ups so as to compare them with the simulation models (see figure 3).

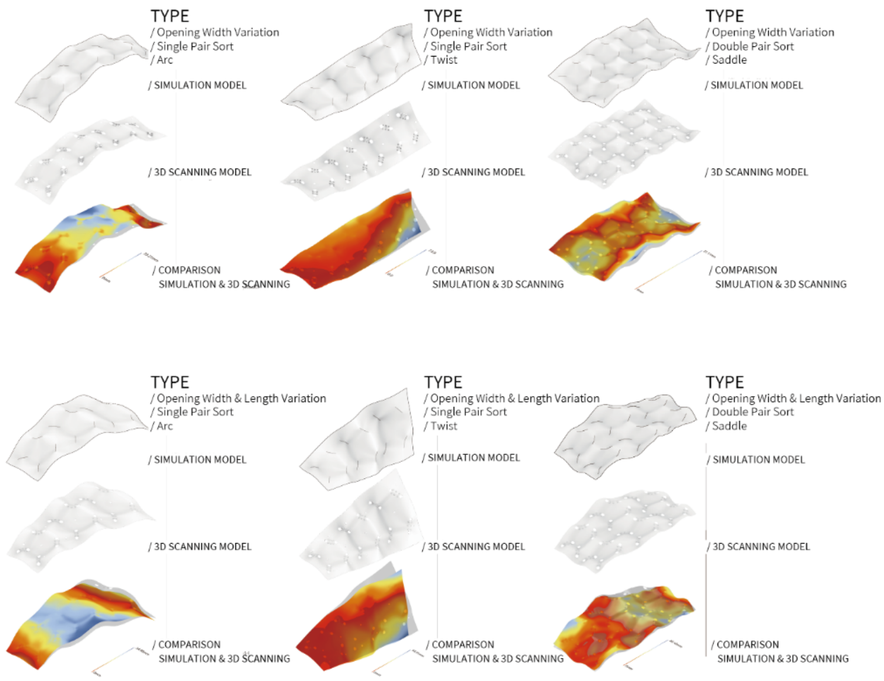

Figure 4. Typical surfaces comparison between simulation real models

2.1.1. Modelling with Mesh Format

This research complies with the simulations of the Miura fold and the bending active panels and uses Mesh as the main format to transfer to particle spring format during the real-time physical-based simulation step, in order to satisfy the physical engine requirements. Mesh format includes mesh vertex, mesh edge, and mesh face. When it comes to origami representation, this research controls the mesh vertex to set up the folded pattern. The folded crease can be represented by the mesh edge and the folded plane can be represented by the mesh face. Next, this research distinguishes between the mesh edge of the peak and valley and the adjacent mesh face of the folded edge, which is crucial for identifying the folded crease of the mesh edge and setting the folded direction in the physical engine. The peak and valley folded direction on the mesh edge is then input into the physical engine, while still strictly keeping a fixed distance between each vertex and restricting each adjacent vertex of each folded face to a planar plane to simulate the physical-based folded behaviour. In sum, using mesh as a digital representation of geometry models provides the opportunity for adding material performance to the geometry model.

2.1.2. Transformation Function Library

To efficiently convert the folding representation into a bending-active model, this research adopts linear regression to build the math function to represent the data library. This data library consists of three parameters, which are opening length, width and deformation angle. First of all, a pair of patterns have been established to simulate the deformation and record the results and then to ascertain the relationship between the opening width and deformation angle. Meanwhile, the endpoints have also been extracted to build the folding representation of this single pair and to measure the folding angle, which comes from the deformation simulation of each width value. The fixed opening length starts from 60mm, and the width gradually increases from 0 mm to 50 mm, 1 mm at a time. Two sets of data, the width and the angle, are acquired. Linear regression has been employed to convert these two sequences into a math linear function with two variables. With this method, the length gradually increases from 60 mm to 160 mm (10 mm at a time), generating a series of linear functions with different fixed lengths. Ultimately, a three-dimensional math function with three variables created by this series of linear functions has been established.

2.1.3. Separation of Geometry and Materiality

The characteristics of the particle spring system allows the material performance to be separated from geometry temporarily and then added back during another stage. This precisely meets the requirement of transformation between origami and the bending-active model. As the Miura fold adapts to the target surface, the elasticity of the model can be extracted and the representation of the folding model can maintain the rigid crease. The value of each local folding angle is then acquired, which can be translated into the opening value through the function library. Following this, a new vertex has been added on each mesh face, strengthening the new relationship with each initial mesh vertex to create a new mesh edge and a mesh face. The locations of these new vertices depend on the values of adjacent folding angles. Moreover, the new mesh face adjacent to the folding crease must be removed to replace the rigid crease with the opening. Afterwards, proper pairs of vertices have been added on the opening edge again to set up the coincidence of opening in the dynamic physical simulation. In the last stage, the mesh has been subdivided into proper densities and the elasticity has been added back to the model to simulate the sewing opening. In conclusion, the separation of geometry and materiality allows researchers to edit and convert the mesh while simulating the bending behaviours.

3. Results and Discussion

3.1. THE PERFORMANCE OF TYPICAL SURFACES

This research aims to analyse the validity of the form-approximation strategy through fabricating typical surface prototypes, and the results confirm that the performance of the strategy corresponds to that of Miura folding, which is shown to work well with typical surfaces such as arches, twists, and saddles.

Firstly, when the material system performs the arc surface, the peak angle and width value of the bending deformation are larger than the valley angle and width value of the bending deformation. Moreover, each pair opening, perpendicular to the bending direction, shows the same value. Then, when the material system performs the twist behaviour, the pairs of peak and valley values obviously have opposite relationships. The values on the right side appear to be larger than that on the left side when twisted deformation takes place. Thirdly, the saddle behaviour demonstrates the trends of performing the typical arc surface in the parallel direction. Furthermore, in the perpendicular direction, the values of both the peak and the valley present a downward trend from the centre (see figure 5).

3.1.1. The tolerance between simulation and physical model

The results reveal that the tolerance between the simulation and the real model is under 30%, which is a direct result of the material simulation method used in this research.

The Live Physics engine used in this research provides an efficient and fast way to explore the deformation of the new strategy. If the pre-stress plays a decisive role in the stiffness of the system, using nonlinear infinite analysis to simulate real physical behaviours and to decrease the tolerance is needed.

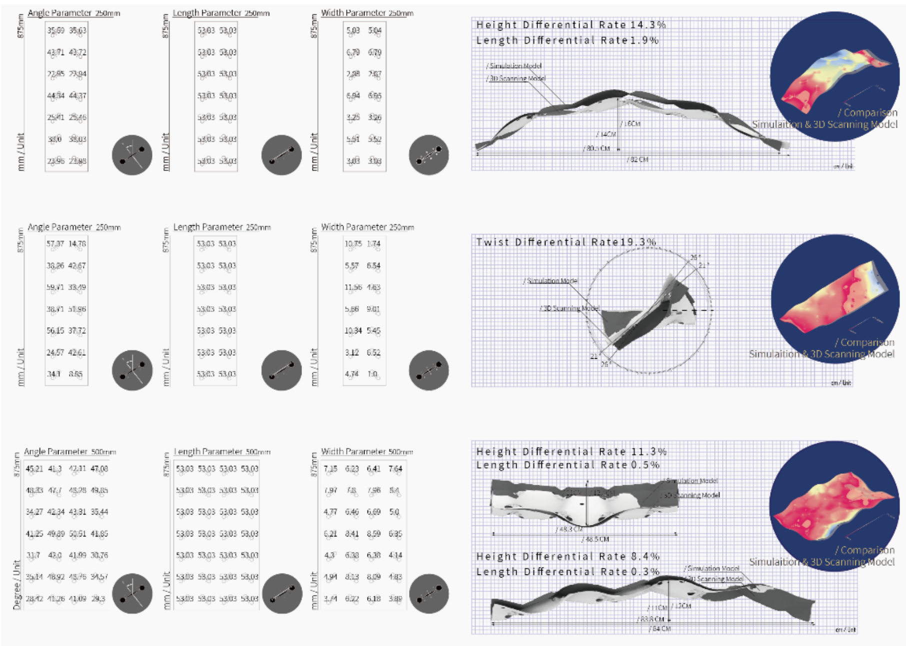

Figure 5. Typical surfaces comparison between simulation real models

3.2. CASE STUDY

The Whisper of Wind is a spatial installation (3.3m * 2.6m * 0.7m) that represents the form-approach strategy on the bending-active system. The shape of this installation demonstrates the performance of the arc, twist, and saddle (see figure 10). All 16 panels (90cm * 60cm each) are rolled and put into a bag (60cm * 35cm * 35cm), relying merely on a motorcycle for transportation (see figure 6).

While assembling the panels (see figure 9), the gaussian curvature visualisation of the digital twin is referenced to determine whether the opening is a peak or a valley (see figure 7). For instance, the colour red represents the negative gaussian curvature, which means the opening is a valley bending, and the colour blue represents the positive gaussian curvature, which means the opening is a peak bending. Three pairs of holes are located at the extensions with a fixed distance from the edge of each opening and are locked with fixed-size plastic bands and rivets (see figure 8).

The design process of using Miura fold as a representation model starts with planar. The border of panels is controlled in the module aluminium sheet while the pattern is being built. During the step of laying out units on the module materials, only the openings and the corners are wasted. Conversely, for the form-approximation strategy that uses the origami model to undergo the coupling process, there are some restrictions to be cautioned, such as the need for the folded direction of each pattern to be maintained while the complex shape is being explored

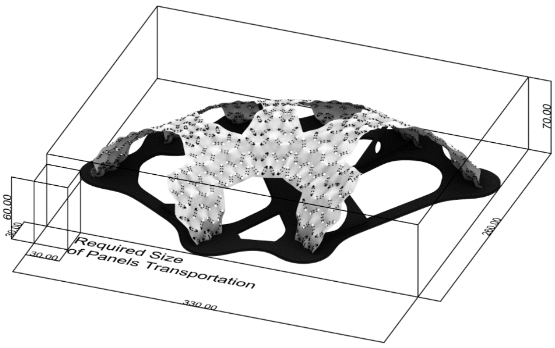

Figure 6. Size of Transportation panels and installation

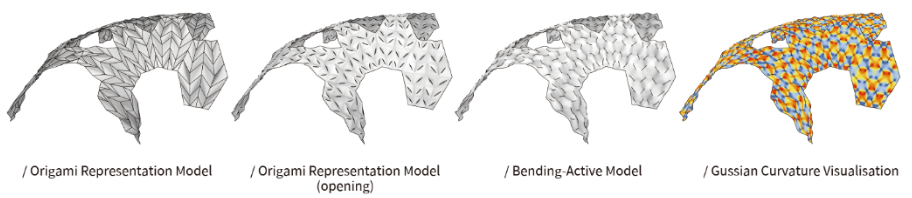

Figure 7. Size of Transportation panels and installation

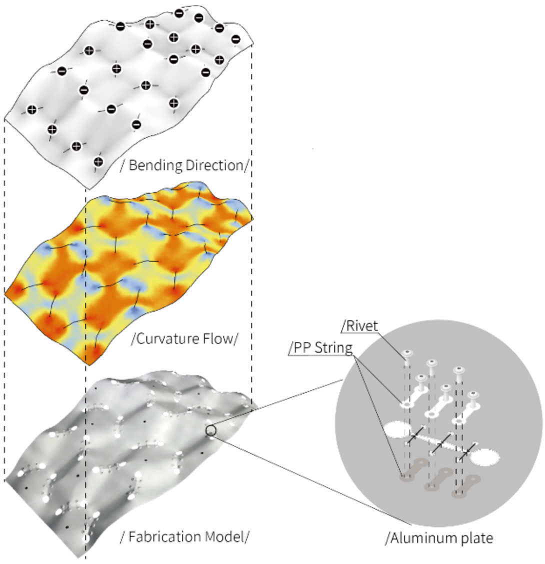

Figure 8. Deformation of unit assembly

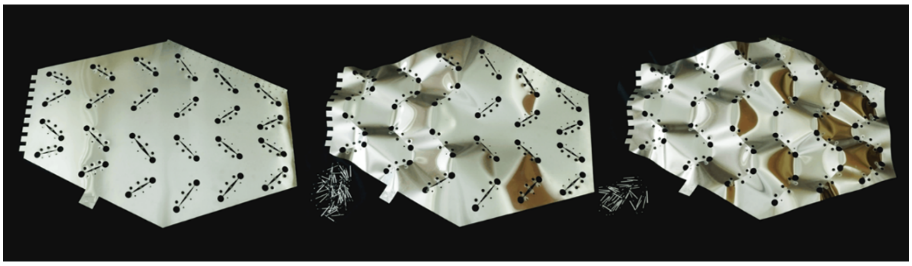

Figure 9. The assembly process of the pattern panel

Figure 10. The result of the installation

4. Conclusion

In conclusion, the self-built case uses the Miura fold pattern to validate the idea of utilising the form-approximation strategy for bending-active design. When compared with the form-conversion strategy for plate systems, the form-approximation strategy seems capable of controlling the deformation of the plate merely through sewing the patterns of opening. Moreover, using origami as a representation model that starts with planar makes for more controllable panel borders. While laying out units on the module materials, the amount of material wasted is evidently lower. Conversely, for the form-approximation strategy that uses the origami model to undergo the coupling process, more obstacles are bound to surface as designers explore this complex shape.

On the contrary, when performing the convex surface, a bigger pattern scale is needed. Designers must take into consideration the elastic performance of the material in order to avoid the permanent elastic deformation. This performance is directly associated with and influenced by the performance of the adopted origami pattern.

It is believed that the case study presented in this research and the design strategy of form-approximation will provide fuels for future researchers to further explore patterns-based application through elastic bending.

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