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FlexMaps Pavilion: a twisted arc made of mesostructured flat flexible panels

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Abstract

Bending-active structures are able to efficiently produce complex curved shapes starting from flat panels. The desired deformation of the panels derives from the proper selection of their elastic properties. Optimized panels, called FlexMaps, are designed such that, once they are bent and assembled, the resulting static equilibrium configuration matches a desired input 3D shape. The FlexMaps elastic properties are controlled by locally varying spiraling geometric mesostructures, which are optimized in size and shape to match the global curvature (i.e., bending requests) of the target shape. The design pipeline starts from a quad mesh representing the input 3D shape, which defines the edge size and the total amount of spirals: every quad will embed one spiral. Then, an optimization algorithm tunes the geometry of the spirals by using a simplified pre-computed rod model. This rod model is derived from a non-linear regression algorithm which approximates the non-linear behavior of solid FEM spiral models subject to hundreds of load combinations. This innovative pipeline has been applied to the project of a lightweight plywood pavilion named *FlexMaps Pavilion*, which is a single-layer piecewise twisted arc that fits a bounding box of 3.90x3.96x3.25 meters.

Keywords: bending-active, form-finding, simulation, twisting, plywood CNC, spiral, piecewise

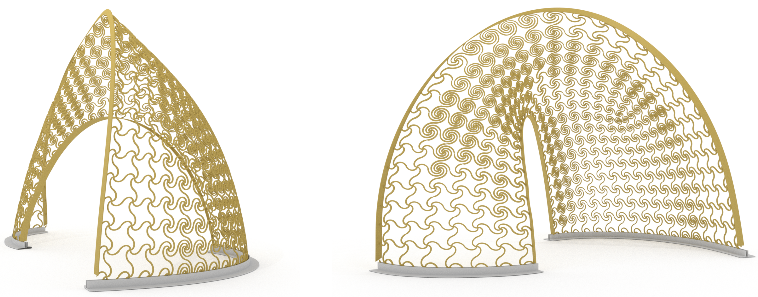

Figure 1: Overall view of the assembled plywood FlexMaps Pavilion made of bent flat panels.

1 Introduction

Bending-active structures produce efficiently complex curved shapes made of flat or straight elements [1]. In the past, such structural systems were based on empiric techniques to produce curved geometry efficiently and cost-effectively. Nowadays, the availability of simulation techniques gives control of form-finding and verification processes of such lightweight and efficient structures [2]. If in the past the main advantage was to have a cheap technology to build even doubly curved surfaces, now the main reason to adopt this technique lies in the reduced weight and the economy of producing flat panes regardless of their curvature.
The bending-active technology characterizes different structural types such as plate shells [3], hybrids composed of membranes with elastically bent battens [4], and various types of adaptive and elastic kinetic structures [2].
The workflow adopted for the FlexMaps Pavilion uses a fully integrated approach [1] for the definition and the control of the mesostructures (base geometry) and consequently of the material behavior. However, the main innovation of the present approach is that the shape obtained by numerical form-finding results as close as possible to a predefined target geometry. This is a step towards a designer/artist-oriented tool.
Another novelty lies in the assembly. In post-restrained structures (where the components are bent and fixed to the ground), a common approach is to post-tension of the overall shape that initially lies in the flat position. Conversely, the FlexMaps approach is based on bending and assemble the single mesostructured element, which lays flat in the rest configuration. Its final shape results from internal elastic forces that arise when connecting progressively the spiralling elements. Thus, only a minimal amount of bending energy is required because of such a step-by-step construction sequence. If an easy fabrication is obtained by producing a flat segmented array of panels, a further cost-saving characteristic of the FlexMaps Pavilion may be found in its assembly procedures.
The main issue of bending-active structures is that the elastic bending causes initial stress. This lowers the stress reserves that the structure may attain due to external loading. The spiral geometry, which is the main idea behind the present project, tackles this point. First, having a spiral path instead of a linear path brings to minor bending stress for the same curvature. Second, the spiralling geometry can be modified to obtain bespoke FlexMaps panels in order to accommodate local curvature demands, consequently varying the bending stiffness and preserving a uniform initial stress on the panes. This approach corresponds to design custom mechanical properties without changing the material but only by acting on the geometric parameters of spirals [5].

2 FlexMaps concept

The technique presented in [5] is designed to physically approximate an input 3D shape by interlocking a set of fabricated flat panels which are coupled solely by snapping together connectors on their boundaries. Following Flexmaps [5], a generic input shape is flattened on a 2D space, and then it is split into multiple panels. Each panel is made flexible by carving out long thin spiral-shaped structures. The pattern has to be relatively dense and regular enough to be aesthetically pleasing once they are assembled to complete the final shape.
Inspired by the beauty of geometric tilings, Flexmaps uses a quadrilateral arrangement of spatially-varying, four-arm spiralling shapes. The spirals have sufficient degrees of freedom that they can be continuously shaped into multiple configurations by varying three primary parameters: scale, twist, and width. Some settings of the spiral are shown in Figure 2. As

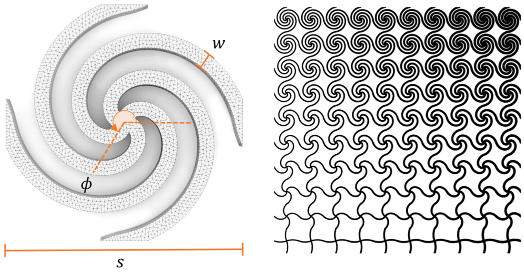

Figure 2: Left: descriptors determining the geometry of our spiral-shaped microstructrures. Right: assemblies made out of spirals can smoothly variate the twist (vertical axis) and width (horizontal axis) of the spirals.

it is possible to observe, the shape can undergo a significant change of forms, and every form corresponds to a particular set of mechanical properties.

This strategy follows a new philosophy of mechanical design of elastic properties that have been recently pursued by several optimization techniques [6]. Fabrication specific small-scale structures can control a large variety of mechanical properties. Distributing different microstructures within surfaces of areas makes it possible to manufacture deformable objects with continuously varying mechanical properties.

In the case of Flexmaps the mechanical properties are optimized such that, once the structure is assembled, its static equilibrium configuration matches as much as possible the desired 3D shape. However, the final shape mainly dependents on two main factors:

Primitive Distribution The panel subdivision and the distribution of the quads that embed the spiral has a great influence on the global equilibrium position of the entire Flexmap.

Shape of the Spirals The mechanical properties of the Flexmap can be controlled on a local basis by the varying shape of the spirals. While the underlying quad tessellation fixes the scale, twist and width can be adapted to match the desired flexibility.

The central core of the optimization process is a data-driven model that can predict the resulting deformed shape in 3D at interactive rates. The mechanical model is based on the rod coupling formulation in [7] and allows to approximates the range of spiral deformations with sufficient accuracy at an interactive rate.

The panel layout is initially derived using a state of the art algorithm [8], and then it is iteratively optimized by merging adjacent panels. This iterative optimization process tries to minimize the difference between the target shape and the predicted equilibrium shape computed by the physical model.

FlexMaps allow to design elastic surfaces with heterogeneous material properties, then the parameters of the spirals can be optimized to match the target shape at the equilibrium configuration. Intuitively, regions of high curvature of the mesh should be populated with characteristically compliant spirals. However, the equilibrium configuration is the global results of all the mechanical properties of the spirals and the boundary conditions they must satisfy. The optimization of this objective is a complex iterative process that minimizes non-linear energies and that matches a set of linear constraints to ensure the shape to be in equilibrium (details of this process are in [5]). An overview of the entire processing pipeline is shown in figure 3.

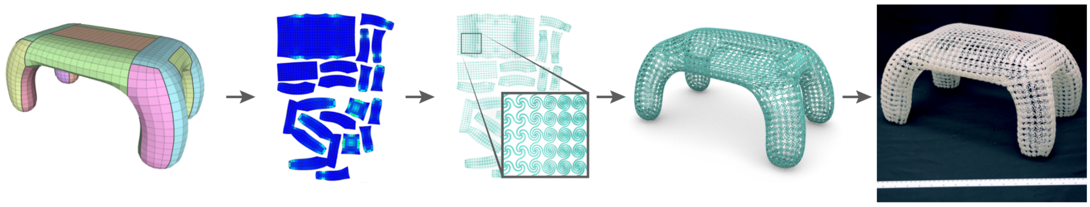

Figure 3: An overview of Flexmap modelling pipeline: An input mesh is split into multiple patches composed by quads; The patches are mapped on a 2D domain; A special spiral-shaped microstructures is embedded on each quad; The parameters defining the shape of spiral microstructures are optimized to improve accuracy in the final representation.

3 Design of the FlexMaps Pavilion

The flexmap Pavillon is a twisted lattice surface that is anchored on the ground. Base sections are inward-bent arches. The shape has been selected to be a challenge in both geometric and architectural terms. Moreover, the shape delimits a space but also allows people to walk through it. There is a sufficiently-wide curvature range and no symmetry. The dimension of the bounding box are 3.90x3.96x3.25 meters.

3.1 Form finding and segmentation

The twisted shape has been modelled manually. Then, it has been re-meshed with a quadrilateral meshing following the approach based on global parametrization proposed in [9]. The initial quad meshing is an essential step in the overall modelling pipeline since it defines the dimension of the spiral. In fact, each quad is used to embed exactly one spiral. The initial cross-field that drive the parametrization is aligned with the boundaries and smoothed in the shape interior. Then, the shape of each quad is further optimized using the approach proposed in [10]. This optimization step is fundamental to ensure each spiral to be embedded in a regular quad. In case this is not verified, significant non-rigid deformations might introduce an unexpected mechanical behavior in the embedded spiral.

Due to fabrication constraints, target quad edges of $0.25m$ have been selected. Moreover, for aesthetic reasons a constant width of 15 mm and a twist range of $100-250°$ are chosen as input parameters. The upper twist limit has a further aim to avoid too dense spirals, which may result too close with respect to the milling tolerance.

FlexMaps panels segmentation is user-defined since the earliest design phases and guided by the constraints of fitting six boxes each with a maximum external size of 1x0.75x0.65m and maximum weight of 32kg. Finally, a total amount of 75 panels are generated, each grouping two up to six spirals.

3.2 Materialization

The 2D FlexMaps panels are laser cut from Okumé plywood panels. The material has been selected according to the indications given by [11] and [1]. Particular attention has been dedicated to the recommended limitation $\sigma_{M,Rd}/E > 2.5\ MPa/GPa$ for actively-bent structures, which in this case equals $46/4.41 = 10.43\ MPa/GPa$. The ground edges are clamped in a CNC cut plywood profile; moreover, they are mutually connected and tied down. The naked edges that form two crossed arches are out-of-plane stiffened using a segmented laser cut plywood plate. The role of these arches is to provide additional restraint to the panels snapping in the assembly

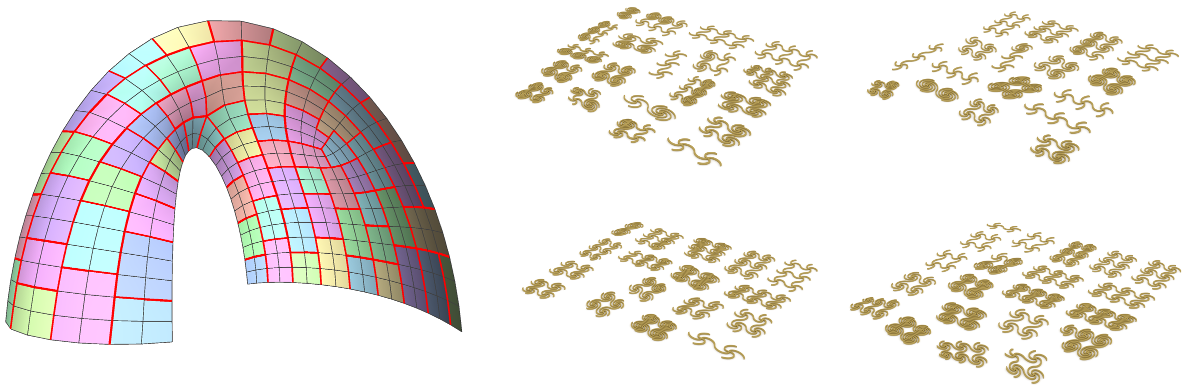

Figure 4: Pavilion patches: schematic view of the Pavilion highlighting the seams and the initial quad mesh; flat spiralling FlexMaps panels

phase.
To connect FlexMaps together connectors are encoded within the computational framework and are made of interlocking shapes, additionally secured by screws.

Table 1: Okumé plywood material properties (technical data from the manufacturer)

Nominal thickness (mm)	Num. Strata	Density ρ (kg/m^3)	Young's modulus E (N/mm^2)	Bending strength f_k (N/mm^2)
15	7	500	4410	46

4 FE Simulation

For the detailed deformation and stress verification of the Pavilion a fully nonlinear solid model has been built and anlyzed in the ANSYS package [12]. The verification consists of two phases: the first one to model the individual assembly of the panels and their initial stress; the second one to model the overall behaviour under external loading, such as gravity. Linear isotropic material properties according to Table 1 are used. In the first phase, each flat panel is rigidly moved in a position that is as closest as possible to its deformed shape. This placement aims at improving the convergence of the analysis. The deformed shape is deduced from the form-finding phase. Then, a displacement is imposed at the extremes of the spirals' free arms to bring them in their deformed position. Consequently the FlexMaps panel assumes its pre-stressed configuration.
The individually deformed (pre-stressed) panels and the accompanying stress fields are exported in a second environment in which the panels extremes are coupled, and boundary conditions are applied. In this setup, the structure is released and gravity and other external loading are applied.

5 Fabrication and assembly

The FlexMaps panels are CNC cut in the shop by means of double precision mill to accommodate tolerances of the interlocking shapes of connectors. The connectors have been previously tested in a four point bending setup to obtain a quantitative estimation of the stiffness reduction caused by the connection.

The Pavilion is assembled section by section going from one support to the other, sequentially bending and fastening each FlexMaps pane. Moreover, these patches are spliced in a staggered configuration to minimize the bending energy that is required to keep the Pavilion section in place. To this purpose, the crossed arches play a fundamental role in providing a restrain also during the assembly. Vertical supports and cross-section springs provide additional help in this phase.

6 Conclusion

The FlexMaps Pavilion proves that it is possible to effectively use mesostructured panes to build lightweight bending-active structures in which the initial stress is very low. The major advantage of the form-finding approach provided by the FlexMaps algorithm is to match the curvature demands of the target shape by varying the geometrical parameters of the spirals. Thus, even complex shapes such as the twisted arch pavilion becomes feasible. The FlexMaps approach can be applied for the design of a complex pavilion, which results a feasible structure.

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