Curved-crease paperfolding shell

Given the geometric constraint of curved-crease paperfolding which type of shell can be designed and fabricated that uses a single surface folded along curves with compliant hinges? This research project resulted in building a shell based on curved folds, specifically mirror reflections of a general cylinder. The structure was realized with vulcanized paper, a material that becomes malleable while moist. This enabled a building process in two phases, the first while the material is wet and foldable, and the second when the paper pulp dries and hardens.

Keywords: *curved-crease paperfolding, compliant hinges, single-surface shell*

The requirements that created the context for this project are based on a Foundation grant which afforded us to construct this project during a course in an undergraduate school of architecture. The pedagogical ambitions frame the project in the sense that participating students are supposed to learn problem solving by realizing a small structure at full scale. Regarding the material choice and technique of construction we imposed additional constraints. The material should be readily available, low-cost, non-toxic during fabrication and fully recyclable. The ambition is to find a material that is not typically used in construction as to insure innovative solutions during the detailing phase of the project. Another main constraint is that the structure had to be made by folding the entire surface into its final configuration at once. We used a simple array of strings and pulleys to lift the surface and fold it into its final configuration.

Geometry of curved creases

Curved creases have been explored by artists, designers and geometers since the 16th century when table decorations consisted of elaborate arrangements made of cloth napkins (Juan Callas). Josef Alber's students used curved creases in his 'Vorkurs' At the Bauhaus and since the 1960's (Josef Albers). We should consider the work of David Huffman, Ron Resch, Poul Christiansen, Hiroshi Ogawa and Kurt Londenberg. In more recent years origami artists and computational folding experts have further explored curved creases, but there exist very few examples at the scale of a pavilion that architects could learn from. There are few types of curved creases we can model in 3D software, as we still don't know of a general mathematical description of the behavior of a curved crease. Mirror reflections of cones and cylinders are however relatively easy to construct with CAD software as the rulings are known in the flat and the folded state. Another significant advantage is related to working with curved surfaces in 3D rather than editing a crease pattern in 2D. We used ORI-REF for initial studies (Jun Mitani) and also simulated abstractions of the design using FreeFormOrigami (Tomohiro Tachi) in order to study the folding motion.

Design Strategy

Since the design is based on mirror-reflecting general cylinders in 3D, it was relatively easy to iterate through many versions and make paper models at every step. The input surface, the general cylinder that is used at every step to generate the curved-crease, can become visually more dynamic by misaligning the rulings with the main directions of the arch-like pavilion. Aesthetic decisions related to the final configurations were agreed upon as a team and several one-week competitions were used as a format to aid in a collective decision making process.

FEA and strategy for location of ribs

The finite element analysis shows that substantial forces occur along the creases. Tension forces concentrate in some areas along the bottom of the surface. The tension and compression forces in the surface appear reasonable given the properties of vulcanized paper within the areas that are further away from the creases, but the moment forces in the compliant hinges clearly require stiffening of the folding angles. The constructed solution relies on 4 main ribs and 2 series of linear stiffeners. The stiffeners are located in 2 planes and their location is optimized such that they cross through creases with large angles.

Surface material and devised details

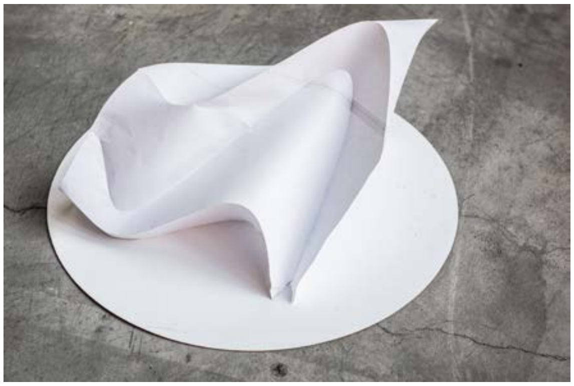
Vulcanized paper was invented as one of the first plastics. Paper pulp is treated with acid such that the bonding properties between molecules change. The result is a paper-like product that is stronger. The paper is malleable while wet and can dry in a deformed state. We used this property to fold the creases while the material was soft and then waited for the creases to harden. Vulcanized paper recyclable in the US, but this may not be the case in other countries.

Compliant hinges have several advantages and disadvantages in the context of fabrication and a building sequence. The advantages relate to folding accuracy, position control and material continuity in terms of force transfer in the surface. We address the constraint of assembling the entire surface before bending it in the following way. The compliant hinges can be folded while wet and can dry in the correct position once the ribs are attached to the surface. After much iteration of perforation patterns for the hinges, we decided to use material continuity that has a 4 : 1 ratio of length to surface thickness. This ratio resulted in very few failures during the folding process.

Discussion

We identified several issues and areas for improvement. The structure showed damage by delaminating sheets in the high-stress areas of the FE analysis. This means that the surface to surface connections should have been designed with tension forces in mind. Creating compliant hinges that bend during the building process, but take on moment forces once folded, is a difficult problem. Future work should investigate stiffening of folding angles without continuous ribs. The floor rail proved useful during the building process but should be designed to take on tensile forces.

Regarding the pedagogical framework and execution of the project the reviews and internal school assessment show that the project was a success at that level.



Paper model of final design

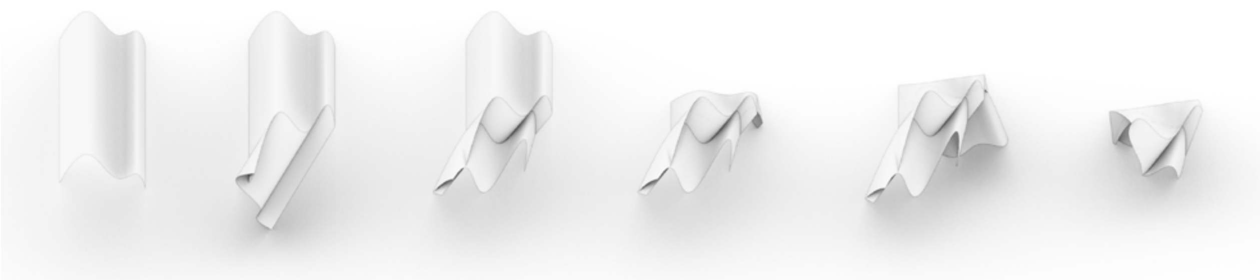


Diagram of design process that is based on five mirror reflections

View of final pavilion

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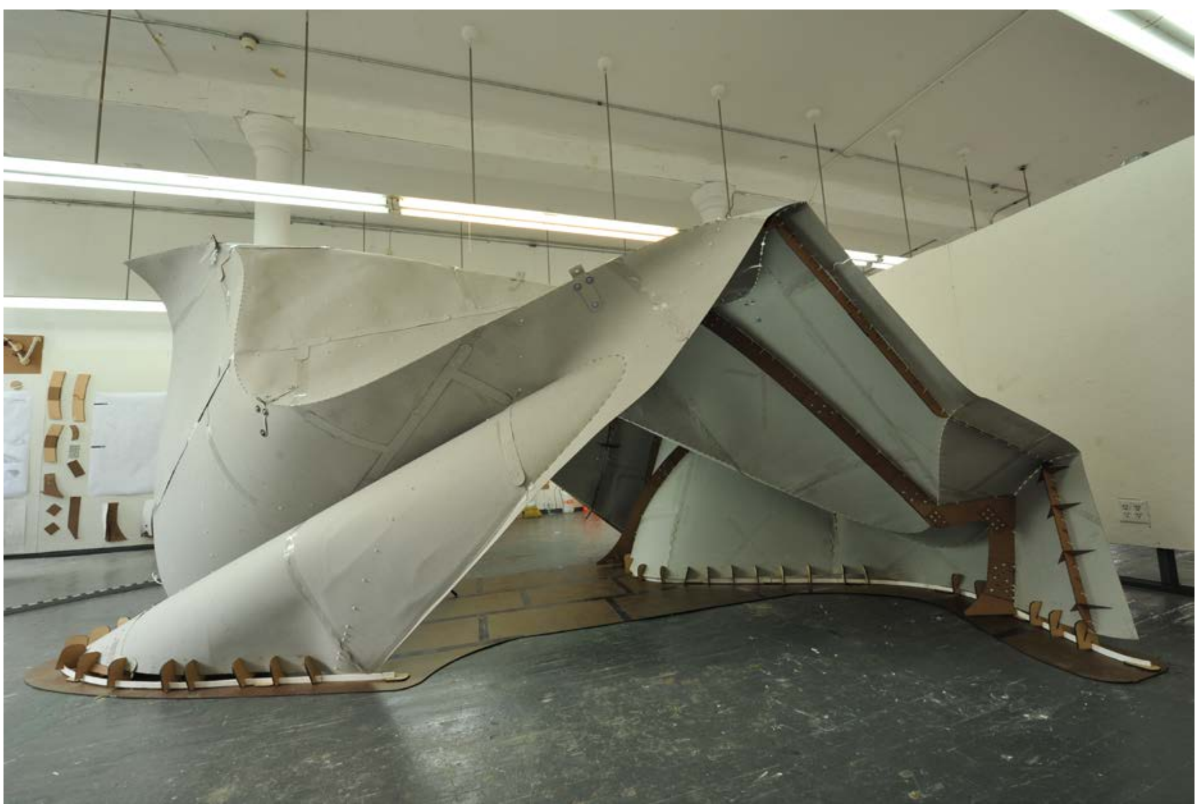

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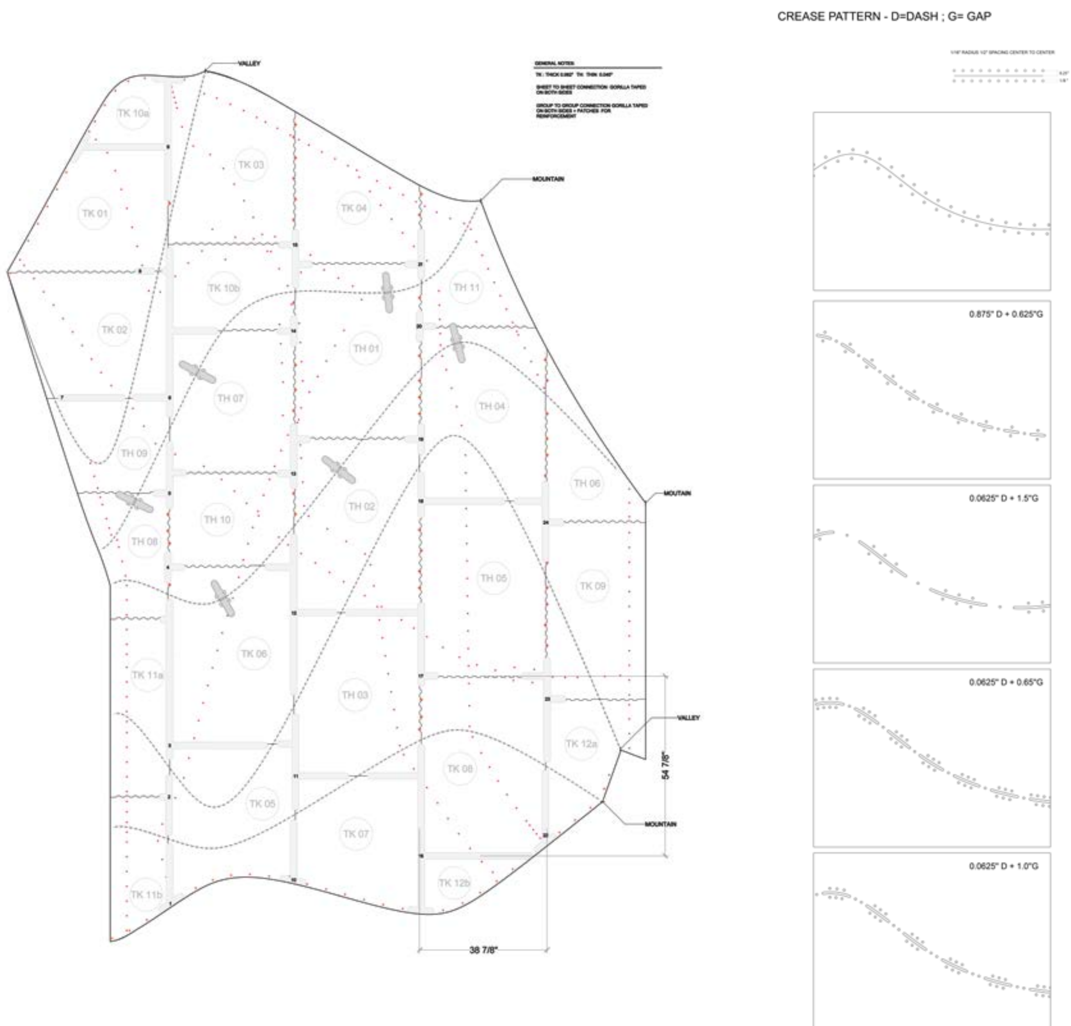
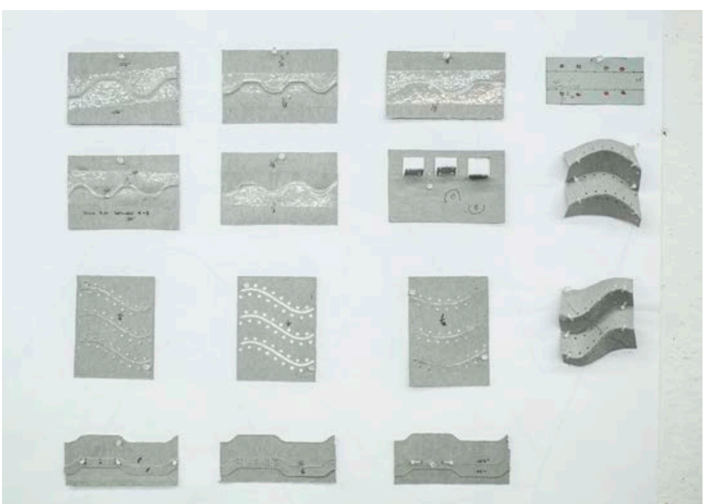
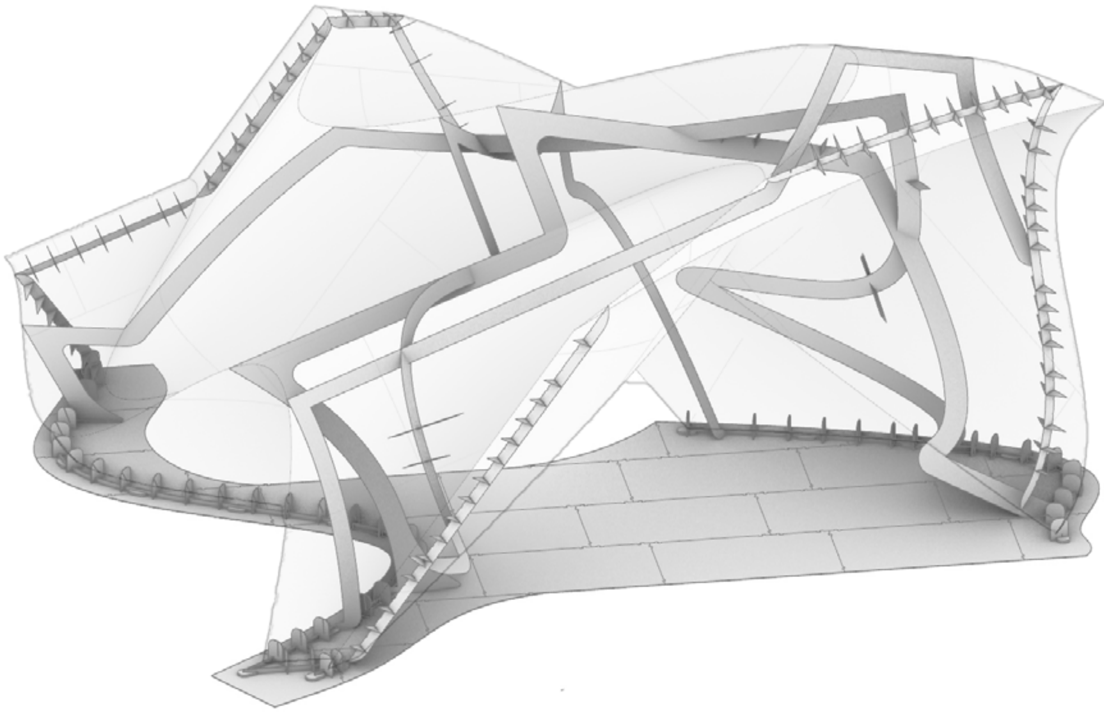


2D drawing of all components with crease cuts and surface to surface connections / compliant crease tests



Examples of milling test



3D model with angle stiffening ribs

Detail view of final pavilion with different rib details