Curved-crease Cardboard Origami: A Framework for Modular Deployable Cardboard Structures

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ABSTRACT: This paper explores the use of curved-creased Origami to create complex architectural forms from corrugated cardboard. Curved-creasing blends folding and bending through curvilinear creases, transforming flat sheets into load-bearing 3D structures. While this technique has been applied to materials like paper, aluminum, and plywood, its potential with cardboard remained unexplored. The study used digital simulations, physical prototyping, and mock-up assemblies to test ten design templates, focusing on minimizing cuts, avoiding wrinkles, and ensuring structural stability. While simulations predicted stress points, physical prototypes revealed that cardboard naturally releases stress through wrinkles along its corrugation channels. To address this, researchers introduced supplementary and stress-releasing fold lines, controlling deformation while enhancing the material's aesthetic qualities. Findings demonstrate that curved-creased Origami can expand the architectural potential of cardboard, offering a sustainable, low-carbon alternative for design applications.

KEYWORDS: Curved-creased, origami, cardboard, modular, lightweight

INTRODUCTION

Current efforts in the building industry are directed towards reducing its carbon footprint and negative impacts on the environment. Alternative construction materials, such as corrugated cardboard, have great potential due to it being highly recyclable and inexpensive (Schütz 2018; Latka 2017). Carboard has been popularized as a building material by architect Shigeru Ban and can be used to build active vector structures such as columns and beams, and active surface structures like folded panels and wall (Diarte and Shaffer 2021). Surface active structures include folded flat cardboard surfaces, whose efficiency depends on the form of the surface in relation to the forces applied to it. Curve crease folding, unlike traditional Origami composed by straight-line folds, utilizes curvilinear creases to create complex three-dimensional forms. Curve-creased folding has been used in several materials such as paper, metal and composites; however, much less is known of the potentials of this technique to create inexpensive deployable structures with corrugated cardboard. This study seeks to fill this gap by developing and testing fabrication workflows for curve-creased corrugated cardboard deployable structures.

The work presented in this article is based on and expands upon two threads of the literature: First, on the use of Origami and curved Origami for developing architectural systems. Second, this study also contributes to the literature of cardboard as a resource for designing and fabricating low-carbon building systems. The next few paragraphs provide an overview of these two areas of inquiry.

Origami has been a source of inspiration in architectural design as not only a way to construct aesthetically appealing forms, but also as form finding technique for deployable structures. Origami folding allows for creating complex three-dimensional structures from flat sheets and can be designed to achieve desirable material properties such as auxetics, nonlinear, and multi-stability (Li et al. 2019). Additionally, Origami and Kirigami shapes can exhibit enormous resistance to support loads. Previous research done by Wang et al. (Wang et al. 2020), for example, designed an interweaved Kirigami extension assembly with paper, and after different mechanical tests discovered its super strength–load to weight ratio around 10^4–due to the in-plane compression resulting from the overlapped flaps. The most used techniques in Origami rely on straight lines as in the Miura-ori pattern used by Liu et al. (Liu et al. 2015) and comprehensively studied by Miura (Miura 2009). There is also no-crease folding technique by Jackson (Jackson 2011) aimed at creating complex convex to concave curves on paper and later translated to aluminum sheets by Patkau et al. (Patkau et al. 2014). Curve creased folding on the other hand, makes use of curvilinear creases to guide the sheet fold, resulting in a hybrid between folding and bending, unlike traditional Origami which is pure folding (Demaine et al. 2011). David Huffman's curve creased models are perhaps one of the most well-known early examples of this technique –for instance, his Hexagonal Column with Cusps also shown in (Demaine et al. 2011).

In architectural design, curve-creased folding has been used in a variety of applications. The designs can be divided into kinetic and static building components. In the first group, curve crease folding is used as the base geometry for shape-morphing structures, which enables complex geometric transformation. Examples of kinetic systems using curve-creased folding are the climate-responsive facade system by (Tahouni et al. 2020) using 4D printing, an adaptive facade shading system by (Vergauwen, De Temmerman, and Brancart 2014), and Flectofod –a compliant shading device by (Körner et al. 2018). The second group of applications are the static building components that make use of curve-crease folding. One well-known example is the multi-panel sculpture by Zaha Hadid Architects at the Venice Biennale 2012 (Bhooshan et al. 2015), which implemented a form-finding method for curve-creased geometries in the fabrication of 500 metallic panels. Another case in which curve-line folding is used to develop (static) building elements is seen in the curved-Origami timber panels by (Buri, Stotz, and Weinand 2011) showing that this technique is also possible to implement in wood. A subgroup in the static applications can be established with curve-creased formwork examples, where the technique is not used for developing finished building components, but rather, to fabricate three dimensional formworks from flat materials such as wax paper (Lloret - fritschi et al. 2022) or plywood and textile hinges (Scheder-Bieschin, Van Mele, and Block 2022).

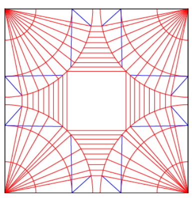
In terms of cardboard, researchers have argued that this material is a lightweight, inexpensive, environmentally positive material for architectural applications (Van Dooren and Verheijen 2008; Łątka et al. 2022). Cardboard structural systems can be broadly classified into active vector and active surface structures (Latka 2017; Diarte and Shaffer 2021). Active surface structures include flat and folded surface elements, such as folded panels, cardboard blocks, and cardboard panels. The folded surface category in cardboard architecture includes Origami folding, an example of this seen for instance, in the cardboard pop-up dome, a lightweight and transportable cardboard structure designed as a multi-use shelter by Latka (Latka 2018). Origami folding techniques can be used to transform flat carboard sheets into lightweight, spatial, and aesthetically appealing self-standing structures: A challenge in using carboard in Origami folding, nevertheless, is the thickness of the material that constrains folding angles, as noted in (Tachi 2011). Curved crease folding, however, has scarcely been explored for cardboard architecture. One example of curve-folding is the curved-fold dome, a geodesic dome made with curve-folded struts (Latka 2018).

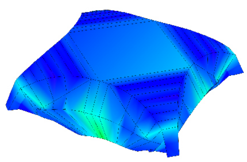
The review of the literature highlights opportunities to expand on existing methods for curved crease folding and cardboard architecture. Several studies have characterized material behavior and presented curve-creasing methods for different materials such as wood, metal, and composites; Cardboard, however, remains largely unexplored. There is a need to develop workflows for transforming flat corrugated cardboard into deployable systems using curve-creased folding to expand its application in architecture. Another critical challenge in using corrugated cardboard for curved line Origami folding is the anisotropic nature and structural directionality dictated by internal flutes, which results in different properties when folded according to the folds' relation to the inner channels' axis.

1.0 Materials and Research Methods

The study started empirically by designing curve creased Origami patterns to make a modular 3D assembly with corrugated cardboard sheets for a temporary indoor construction. The design process included traditional techniques (e.g., hand and digital-made drawings and scaled paper models) and we then implemented quantitative and experimental research methods to assess the process and determine how to improve design and increase fabrication efficacity. Based on the architectural research methods framework proposed by Müller (Müller 2021), the quantitative part of the work relied on digital modeling and simulation using Grasshopper for Rhinoceros 3D and an interactive Origami simulator[1] correspondingly. The experimental part relied on physical prototyping and full-scale construction testing. Table 1 below summarizes details of the methods employed in the study.

Table 1: Research Methods. Source: (Authors 2024)





	Prototyping (Experimental)	Simulations and modeling (Quantitative)	Testing (Experimental)
Goals	Experiment with curved-creasing patterns to fold corrugated cardboard sheets	Investigate and digitally visualize strain occurring on corrugated cardboard sheet due to different types of curve-creased folding angles and patterns.	To build a mock-up of a 3D assembly and asses the construction process.
Study set-up and/or data sources	Digital: Rhino 3D Grasshopper Physical: Fabrication lab set-up using a KUKA robotic arm with a customized creasing wheel.	Digital simulations made with Origami Simulator app by Ghassaei et al. (2017)	Indoor exhibition space and shop at the University of North Carolina at Charlotte, School of Architecture in the USA.
Data collection	Video and photo recording.	Results presented in graphical format and exported as image file.	Video and photo recording.

Data analysis	Visual assessment of strain effects on 3D assemblies for correction of design patterns as well as evaluation of robotic creasing process.	Graphics collected from simulations where visually analyzed.	Observations of assembly process with special attention to procedure, techniques, and tools. Assessment of supplementary building components used in the process.

1.1 Simulation
After designing the Origami pattern in Rhino3D, we simulated the folding process using an interactive Origami simulator. The open access web-based app created by Ghassaei, Demaine, and Gershenfeld (2018) simulates any Origami crease pattern in real-time and helps to understand how it affects the folding. The simulator opens SVG or FOLDS format files and folds paths following a defined stroke color (e.g., red for mountain folds, blue for valley folds, and black for boundary edges) illustrating the axial stresses across the sheet[2]. Stresses are shown in blue (no strain) to red (high strain). We increased the default face and fold stiffness from 0.2 to 1.0 and 0.7 to 1.0 in the simulation settings, assuming cardboard is a much more rigid material compared to regular paper.

1.2 Design and fabrication requirements
A list of prototyping requirements was established in advance to measure whether a particular design was successful or not. These requirements included material and aesthetical criteria such as minimizing the number of cuts on the cardboard sheets, minimize wrinkles after folds, avoid tearing sheets, and facilitate joins between modules to create a potential larger structure. Prototype fabrication requirements included using a tool consisting of a custom-made creasing wheel attached to a robotic arm, no gluing to mount the modules, making a single module per each cardboard sheet, and minimizing waste. All prototypes were made using general purpose and single wall corrugated cardboard pads with flute type C, 4 mm thickness, and 1200x1200 mm dimension3. The selection of this cardboard type was because it can be found anywhere for replicability and strength—its use to provide layers to separate and protect heavy goods of up to 90 kg.

Moreover, inspired in the creasing wheel tools for CNC cutting machines typically used in the textile and packaging industries, we fabricated a custom-made creasing tool with leftover material from the metal shop. We repurposed a 50 mm diameter and approximately 2 mm thick aluminum washer for the wheel and two bearing wheels, a few rubber rings, a 60 mm long aluminum pipe for the shaft, 150x50 mm aluminum profiles, and bolts for support and robot attachment. The main washer-wheel spined freely when the robotic arm moved back and forward, and the angle formed with the cardboard sheet was always 90 degrees. Figure 1a and 1b below shows the initial design and fabricated tool used for the study.

1.3 Template design
Figure 1c illustrates the concept for the cardboard module with three basic parts each on a different color (front, side, and back). The goal was to build a four-point star starting from a square cardboard sheet. The sheet corners would be folded following a series of curved creases and the least number of cuts. The size, position of the curves and distances between them was unknown as well as how many other creasing or cutting lines would be needed to appropriately fold the module. Experimenting with these parameters was the starting point of the prototyping phase.

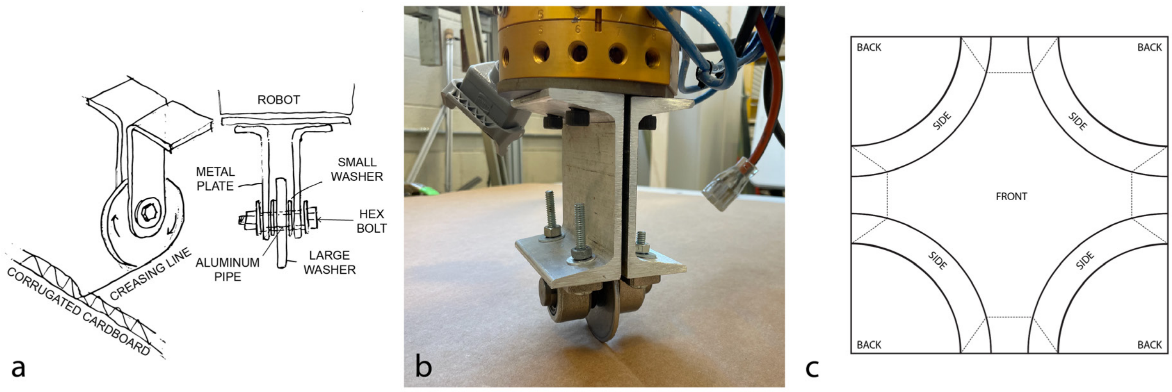


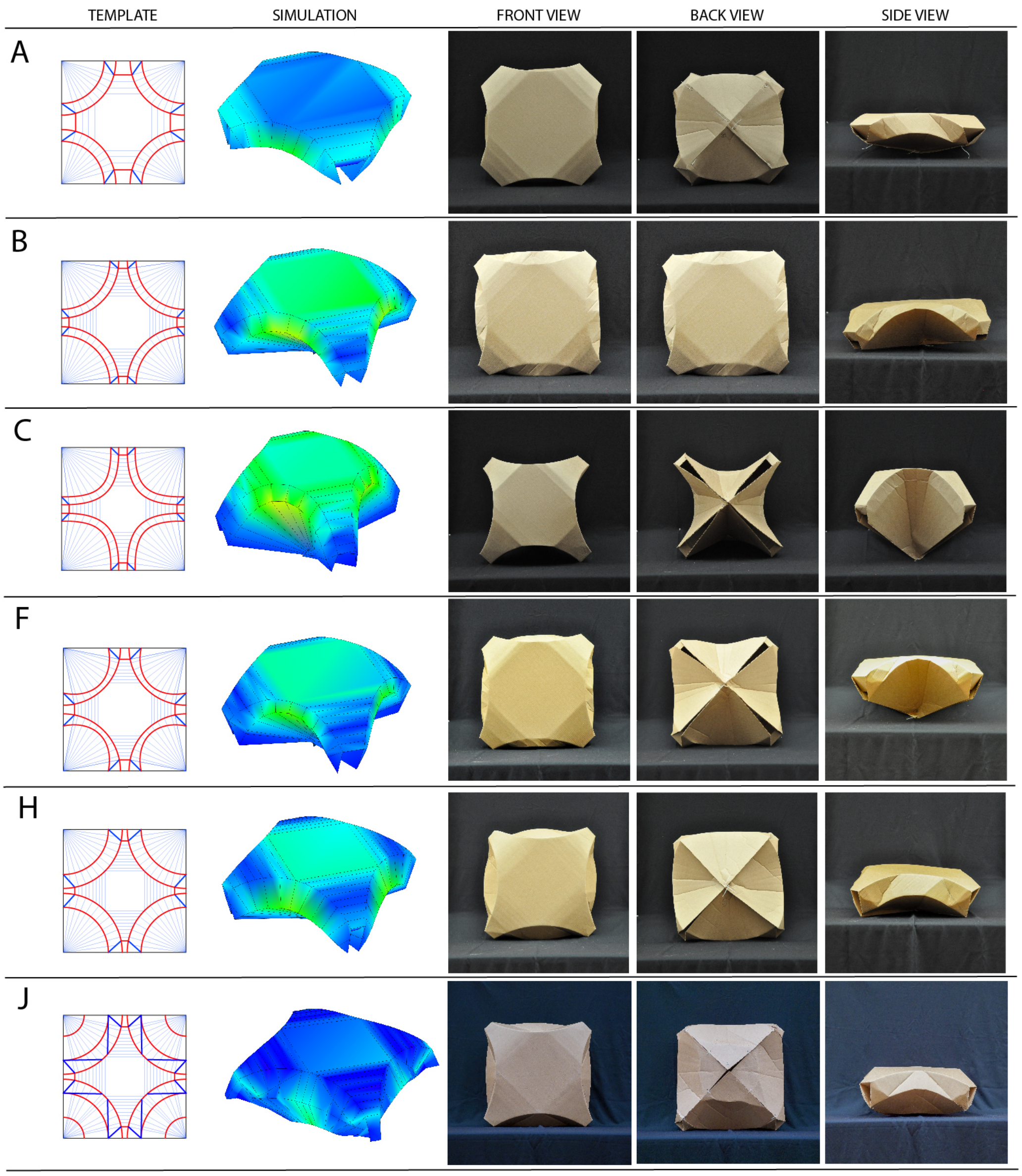
Figure 1: Custom made creasing tool at initial design (a) and final tool (b) and creasing concept (c). Source: (Authors 2024)

2.0 RESULTS AND DISCUSSION

2.1 Prototypes fabrication features
In total, ten template iterations were developed, all of them from cardboard sheets with dimensions 1200x1200 mm. Table 2 illustrates a selection of the most representative including a simulation preview, front, back, and side views of assembled modules. Prototype A parameters were defined intuitively, considering it was the first template of the set. We wanted the tips of the star to be flat not pointed to ease the joins with other modules, so they were approximately 140 mm wide and the offset between the arcs (red mountain folds) on each corner was 115 mm

aiming to give a sizable thickness to each module. After observing the simulation, several blue valley folds were intuitively added to decrease potential face stiffness, especially in the sides and back were strain looked high. We decided to pass the tool twice on the red mountain folds because these are the main folds of the design: the blue valley folds are supplementary folding lines that help guide the folding. Prototype A front, back, and side views show a relatively well-formed module and well-defined star ends; however, the folds in the front were too pronounced and those on sides were uneven and too sharp. In addition, there were several unwanted wrinkles or folds to the side of the module (see prototype A-side view).

Table 2: Prototypes comparison. Source: (Authors 2024)



Experiments for prototype templates B through F sought to study the creasing effects of the arc geometry—here we include images of B, C, and F only. Arcs in these templates have different curvatures and offset distance between them vary from 55-85 mm, the flat end of the star is only 85 mm wide and all of them have 30% more blue valley folds than the first prototype. As it can be seen in the pictures, semi-circular arcs as in prototypes B are easier to fold but even though more blue valley folds where added, the tessellation created on the sides is still uneven. On the other hand, parabolic arcs as in prototype C creates a well-defined front view of the star shape module; though, it isn't possible to completely fold the sides producing a bizarre shape. Prototypes F is template sample that combined semi-circular and parabolic arcs, but still no major improvements were achieved.

Prototype H represent another group of templates with semi-circular arcs separated 135 mm and 85 mm wide flat star ends. Although they were easy to assembly and their front view looked even, the sides had the same problems as in the previous prototypes. Consequently, for the last prototypes, J is a typical example of this group, we added a few orthogonal blue valley folds to release the stresses in the cardboard and purposely guide the folds on the sides. These extra valley folds made a significant difference on how the sides looked. Additionally, prototype J included a minor semi-circular arc in the corners to create a flat surface on the back (see J's back view) and this was the module used to test the mock-up.

2.2 Simulations

Simulations were relatively good on predicting cardboard's behavior. In general, the low strain showed in some prototypes was corroborated during the folding process; however, certain stresses that appeared on the side weren't evident and only visible when assembling the modules. This could probably be solved by correcting the face and fold stiffness simulation settings to get more accurate results. In this regard, an interesting aspect we discovered during the process was the importance of not relying only on the simulation to decide whether to proceed with a template design or not. Both simulation and physical template provided with useful information to take decisions so we would recommend working with both constantly. Figure 2 below shows some examples of problematic stresses that did not show on the simulation but appeared in the physical prototype assembly. Unwanted creases or folds in prototypes G and F and identified in Figure 2a-b with numbers 1, 2, and 3 were solved in prototype J by adding extra valley folds identified in Figure 2c with numbers 4 and 5.

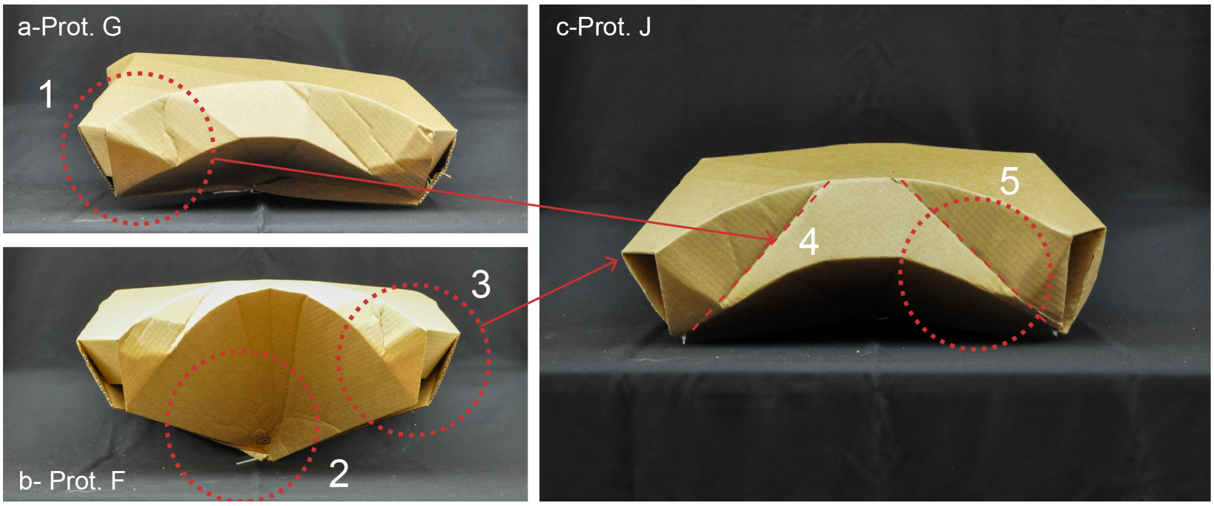


Figure 2: (a-b) Problematic stresses in prototypes G and F and (b) solutions applied in prototype J. Source: (Authors 2024)

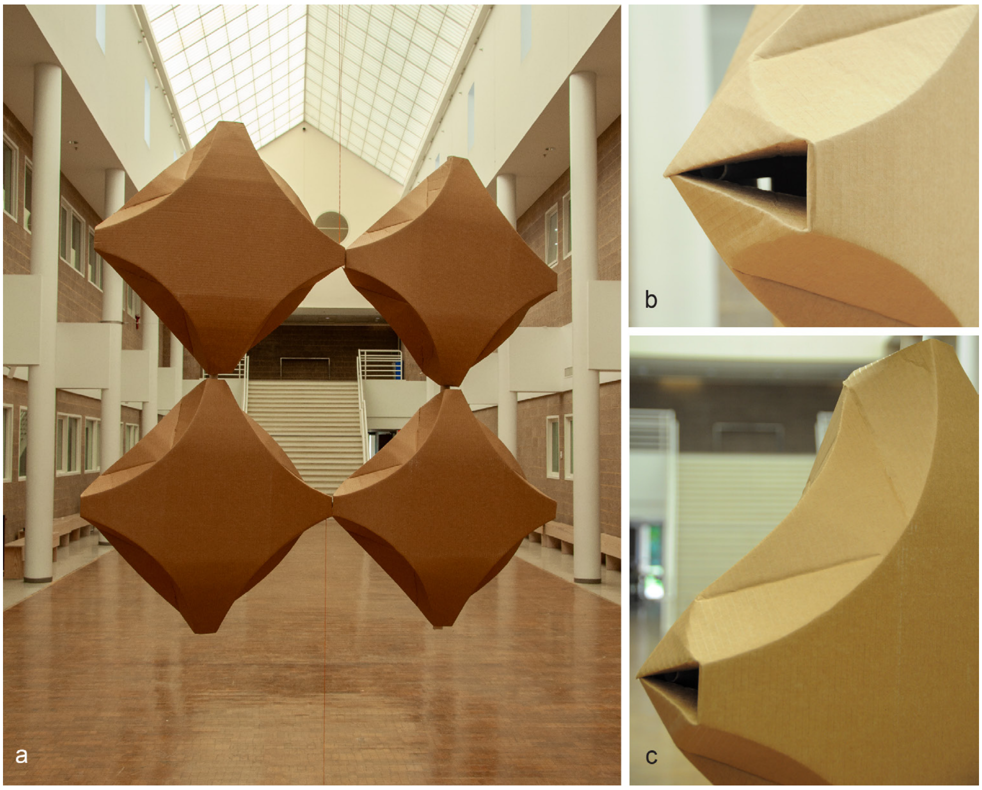


Figure 3: Assembled mock-up with four prototype J modules (a) and folding details (b and c). Source: (Authors 2024)

2.3 Mock-up assembly

Finally, we assembled a structure made with a few modules to test how to connect them (Figure 3a) and explored the aesthetic and spatial qualities of the material system. We then took four prototype J modules, some repurposed PVC pipes 25 mm diameter, plastic ties, and thread. We cut four pipes to the length of two modules and inserted them through the module hole (Figure 3b) to create an internal frame. The four pipes were tied from the back of the modules and hang from the ceiling with a thread. Everything was done by hand and the structure was very light and easy to handle. Figure 3c shows a detail of modules' side where both curved and straight creasing lines are visible decreasing the wrinkles.

The main results can be summarized as following. First, that while the Origami simulator predicted several areas of stress in the curve-creased modules, physical prototyping highlighted the tendency of corrugated cardboard to release those stresses through wrinkles or unwanted creases mainly along the sheets' corrugation channels. The strain or material deformation is evident in the unwanted creases seen, for instance, in Figure 2-a. This behavior is due to the anisotropic condition of corrugated cardboard: the material is composed channels in one direction in between two faces or liners. The template design was imposed on the cardboard sheets and did not consider the structural directionality of the flutes causing warping in some places. Accounting this material characteristic in the template design phase can improve curve-creased folding structures with cardboard. Second, although some template lines did match cardboard structure, some of them still produced unwanted creases probably due to cardboard stiffness. Thus, to help ease the folding process and prevent unwanted folds or wrinkles in the assemblies, one can add two types of extra folding lines: a) supplementary folding lines; and b) stress-releasing fold lines.

The supplementary folding lines are shown in light blue lines in the template column in Table 2 (single pass of the creasing tool) and are mainly put in place to help ease the folding process, making the fabrication of the modules not difficult. The stress-releasing fold lines are shown in hard blue lines in the template column in Table 2 (two passes of the creasing tool) and are put in place to design the strain or deformation, thus helping cardboard into the desired curved-creased assembly. In other words, with the stress-releasing lines one can guide the deformation of the material through fold lines, programming this deformation as part of the design and fabrication. The stress-releasing lines can also be part of the material aesthetic expression of curve-creased cardboard folding (see these details in Figure 3-b and 3-c). Note that this behavior is specific to cardboard, which is thick and stiff, unlike paper, which is more easily folded without exhibiting strain.

CONCLUSION

This study set out to experiment with curved-creased Origami techniques to design and fabricate complex three-dimensional forms made from corrugated cardboard sheets. Corrugated cardboard is an environmentally friendly material made from natural resources and is highly recyclable; however, it's anisotropic material property and particular sandwich type-design makes it challenging for curved creasing folding techniques. The study included qualitative (digital modeling and simulation) and experimental (digital and physical prototyping and testing) research methods. The results of the prototyping and experimentation confirmed the challenges of dealing with the anisotropic behavior of corrugated cardboard in the design of the curve-creased folding pattern. We therefore proposed using two types of creasing lines that are not typically present in curve creased design in other materials: a) supplementary folding lines; and b) stress-releasing lines. These lines helped researchers to program cardboard behavior when template does not match cardboard flutes direction and added a positively aesthetic appeal to the folds.

One limitation of this study was that we only tested the assembly of one module design, however, the use of the supplementary folding lines and stress-releasing lines might also be applicable to other cardboard-crease folding assemblies. The study findings will be of interest of architectural designers aiming at creating lightweight spatial structures with low-cardboard materials such as corrugated cardboard. Future studies will explore template patterns that follow cardboard flutes direction as well as other application scenarios of the curved-creased cardboard technique such as larger spatial structures, enclosures, and ceilings as suggested in Figure 4 below. Despite its exploratory nature, this study offers some insight into the potentials and limitations of curve-creased cardboard architectures, expanding the design language of cardboard as a building material.

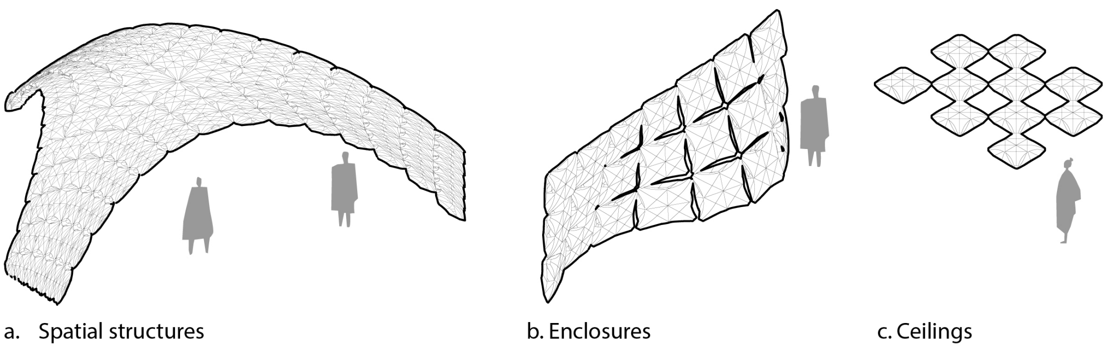


Figure 4: Proposed spatial structures. Source: (Authors 2024)

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ENDNOTES

1 See simulator at https://origamisimulator.org/
2 Other SVG import settings available by request.
3 More information on the cardboard type at https://www.uline.com/Product/Detail/S-3587