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Feasibility of An Origami Pattern Folding for Continuous Manufacturing Process

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Abstract

The engineering applications of origami have gathered tremendous attention in recent years and resulted in many innovative products. Various aspects of origami exhibit different characteristics based on its specific use: the shape changing aspect is used where size is a constraint, while the structural rigidity aspect is critical for lightweight designs. When polymer or metal sheets are processed to have origami creases, they enable significant improvements in mechanical properties. Such light-weight sandwiched structures find extensive use in, for example, the aerospace industry. The work presented explores a novel approach for the continuous production of these folded textured sheets. The method uses a laser etching setup to mark the sheet with the origami pattern. The pattern is then formed by dies and passes through a funnel-shaped conveyor to complete the final stage of the forming process. A simulation approach was utilized to evaluate the method's feasibility and assure structural distortions within acceptable range and avoidance of material failure.

Keywords: Origami; Miura-ori folding pattern; continuous manufacturing; origami-inspired engineering.

1. Introduction

The word origami refers to the traditional Japanese art of paper folding (Gould, 2008; Smith, 2014). Despite the art having existed for centuries, the expanding body of practical applications have only appeared within the last few decades. Rapid growth in computer technology and advancements in mathematical modeling have helped the art to expand into new avenues of expression, from analysis to design.

For centuries origami artists have designed in the highly available medium of paper, producing a variety of folding patterns ranging from statuesque representations of physical phenomena to animated creatures capable of motion. Some designs have the ability to be tessellated, enabling surprising expansion and contraction of the structure. The recent, heightened interest in origami has resulted in the significant advances in developing science (Hull, 1994; Lang, 2018), technology (O'Rourke, 2011) and computational methods (Demaine, 2008) that have a lot of potential in more effectively addressing many modern, complex problems by offering non-traditional solutions.

Origami art offers a lot of potential for influencing future engineering product design, especially in systems where mass, stowed volume, or cost are to be minimized. Such influence may be as indirect as inspiring designers to consider folding in designs or to recognize the possible use of origami approaches in the design of new systems or the analysis of existing systems. But origami also has the potential of being a source of detailed design information. As the potential benefits of origami-based design are becoming more apparent, it is important that resources become available to facilitate the design of origami-inspired systems. They have a variety of applications in diverse fields ranging from medicine to space (Johnson, 2017; Nishiyama, 2012).

Various levels of crease-supporting characteristics exist among available sheet materials. Paper is a well understood medium in the context of creasing. Textiles have become better understood through study into crease proofing and pleating. New manufacturing methods and a recent interest in folded designs of various size scales and materials warrant better characterization of creases in materials beyond paper and textiles. Building on this knowledge helps to characterize the crease properties of non-paper sheet materials, especially polymers and metals, which can expand the possibilities of origami-inspired designs (Francis, 2014).

Use of materials in engineering depends often on their structural geometry and integrity. Buckling and crumpling of thin walled materials, especially used in lightweight and deployable structures, is commonly considered as failure. It appears that these "failure" patterns are common in natural structures and that they have their specific functions - for growth, deployment or stiffening making thin walls better resistant to loading. Modeling experimentally natural origami-patterns by crushing (excessive - and fast - axial loading) or by twisting helps analyzing the underlying geometric / physical rules and leads to novel designs for technical self-deployable structures, for arrays of high stiffness and finally for smart mechanisms including elastic and auxetic properties and anticlastic shapes in materials that initially are inextensible, non-elastic and unable to be curved in the third dimension.

The paper is focused on initial development of a novel manufacturing process suitable for the continuous production of the textured sheets, folded according to the Miura-ori pattern, to be used in light-weight sandwiched structures. The paper is structured as follows: Section 2 reviews recent developments in origami inspired designs, Section 3 outlines manufacturing challenges, Section 4 discusses briefly the folding pattern used, Section 5 reviews sheet material selection. In Section 6 concept of the continuous folding machine is introduced, Section 7 goes over concepts related to sheet forming details, while Section 8 discusses the simulation results. Closing Section 9 outlines future work.

2. State of the Art: Origami-Inspired Designs

Review of origami-inspired designs (Holt, 2017; Morris, 2016; Morrison, 2019) reveal a wide variety of conceptual developments inspired by origami basic tenets, but also indicate that many of them, despite their cleverness are not aimed at mass markets as consumer products, but rather have special use or research-oriented purposes. There are some notable exceptions, such as the Oru Kayak (Grace, 2018), a patented, full-size water craft that can be folded down, when not in use, down to a size of a small suitcase.

Another well-developed application of origami-inspired design found its use in space exploration, and namely foldable antennas and solar arrays (Morgan, 2016).

Foldcore is an origami-like structural sandwich core which is manufactured by folding a planar base material into a three-dimensional structure (Fischer, 2009). These structural elements provide a desirable stiffness/mass ratio, comparable with traditional honeycomb cores. Composite sandwich structures with cellular cores are used in numerous lightweight applications in aerospace, automotive, marine, rail and civil engineering.

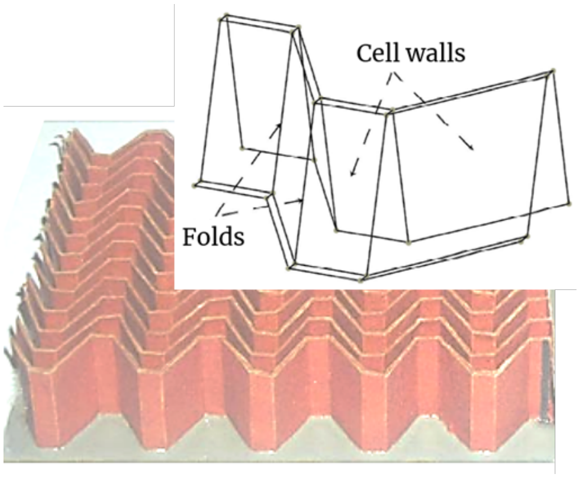

Figure 1. An example of folded core and nominal, single unit cell

Use of origami folding techniques in structural nanotechnology provides an easier and faster way to construct DNA nanostructures with various shapes. DNA origami nanostructures possess abilities to enhance efficacies of chemotherapy, reduce adverse side-effects, and even circumvent drug resistance (Udomprasert, 2017; Ahmed, 2020).

While inspiration transfer of origami concepts to design approaches results in continuously expanding body of literature, the same cannot be said of parallel development of manufacturing methods. It seems that while macro-scale origami objects still rely on already existing production techniques (e.g., manual assembly), micro- or nano-scale developments use additive manufacturing (Johnson, 2017).

An interesting concept for continuous sheet folding was introduced by (Elsayed, 2004). It proposed a complex set of 8 consecutive rollers, which gradually fold continuous sheet of material supplied off a drum. The solution, however, offers continuous folding along one direction only and requires amd another setup for transverse folds.

3. Manufacturing Challenges

Utilization of origami patterns while using industrial materials involves many challenges which do not occur in conventional paper folding. This is because of the thickness and variation in mechanical properties of the materials.

Origami is able to achieve a high level of kinematic complexity. Origami designs can realize great advantages in that they (Francis, 2014):

1. are fabricated from a flat sheet of material,
2. have low friction joints
3. have a low material volume and subsequently have a low mass
4. require only one manufacturing technique (folding)
5. often have great spanning abilities in their configurations ranging from compact to expanded configurations
6. can have higher area moment of inertias than similar curved surfaces rendering them less likely to need structural reinforcement
7. can have controlled buckling
8. often have synchronous deployment that requires few actuation and constraint points
9. can often be tessellated, and
10. can have negative Poisson's ratios.

Materials that have origami-like creases have the ability to both fold and unfold. Hence a material that tends to bend at a previous fold is a material that has origami-like creases. Some materials do not crease (e.g. sheet metal) because they do not exhibit decreased stiffness along the fold. Creases develop when the bending stress is greater than the elastic limit of the material. The formation of a crease resets the elastic memory to a non-zero angle; the harder the crease is pressed, the greater the residual angle (Francis, 2013).

The key manufacturing step is folding the base material into a three-dimensional structure (shown Figures 1 and 2). The folding technique allows different types of unit cell geometries. The main application for foldcores is the usage as structural sandwich cores, resulting in high strength and stiffness to weight ratios. These mechanical properties can be adjusted to the application by varying the unit cell geometry and the base material. Foldcores feature also other multifunctional aspects: good thermal insulation and acoustic damping. Another advantage is the open cellular design, which allows ventilation through the open foldcore channels (Fisher, 2009).

Virtual testing using dynamic finite element simulations is an efficient way to investigate the mechanical behavior of small- and large-scale structures reducing time- and cost-expensive prototype tests. Furthermore, numerical models allow for efficient parameter studies or optimizations (Heimbs, 2008; Liu, 2015)).

One major disparity is that thin materials are assumed to have low thickness. This enables models to be established based on zero-thickness approximations. Conversely, engineering materials like plastic sheets and so on have a significant thickness and come across self-intersection issues even when the fold is done along a single vertex. Another discrepancy is that the creases of thin materials act as hinges due to reduction in stiffness, whereas thicker materials do not undergo such a noticeable variation in stiffness.

The simplest way to eliminate such difficulties is to manufacture using thin sheets as workable material. The challenges on using thin sheets is mitigated by selecting materials that have an acceptable degree of stiffness.

Optimization methods that constitute usage of FEA (finite-element analysis) to distribute mechanical properties for initially flat structures to determine optimal crease patterns so that the desired motions can be achieved are utilized.

4. Folding Pattern

In a novel technique for continuous sheet material folding presented here the sheet material is progressively folded in the two dimensions normal to feeding direction through a set of rollers, followed by a configured roller for the final folding in the third dimension, the two dimensional pre-folded sheet transforms into the final three dimensional folded shape, as it passes through the configured main roller. This method is used to form Miura-ori patterns (Miura, 1989), which offers simple and yet versatile solution. Mathematics of Miura-ori fold patterns and their parametrization for folding process control are omitted in the paper, but the details are available in (Muthukrishnan, 2020).

Figure 3 shows an example of a Chevron pattern (made of paper) generated through a sequence of folding steps. This pattern can also be produced by folding different sheet materials, such as aluminum, copper, stainless steel, Kraft paper, composites and plastics (Francis, 2013).

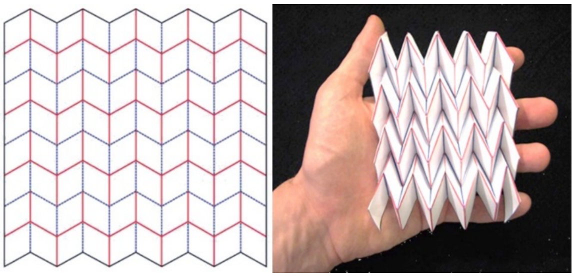

Figure 2. Paper-based model of the Miura-ori pattern.

5. Material Selection

The selection of materials is an ordered process by which engineers can systematically and rapidly eliminate unsuitable materials and identify the one or a small number of materials which are the most suitable.

When the objectives and constraints can be expressed as well-defined limits on material properties or indices, systematic selection by analysis is possible. When constraints are qualitative, solutions are synthesized by exploring other products with similar features, identifying the materials and processes used to make them. When alternatives are sought for an existing material and little further is known, the method of similarity – seeking material with attributes that match those of the target material – is a way forward. And many good ideas surface when browsing. Combining the methods gives more information, clearer insight, and more confidence in the solutions.

The Material Index (M) for a panel (flat plate, loaded in bending) stiffness, length, width specified, thickness:

$$M = \frac{\sqrt[3]{E}}{\rho} \tag{1}$$

where E is Young's modulus for tension, the flexural modulus for bending or buckling; and ρ - density.

A selection was carried out with CES Edupack software (Ashby, 2014). From a generic materials database, a tailored custom database was generated, which includes polymers, metals/alloys, and composites. Straight line shown in Figure 3 corresponds to Eq. 1 and is a selection boundary.

For conceptual prototype, the initial consideration was on forming origami sheets utilizing polymers as the feeder material. As a result, the material was chosen to be Polycarbonate (PC). The choice was driven in part by sheet availability and low cost of the material.

6. Conceptual Design of the Continuous Folding Machine

The concept of the continuous folding machines integrates the key elements of the manufacturing process, which consists of the four stages shown in Figure 3.

6.1. Pre-processing of the Sheet

The Polycarbonate (PC) sheet roll that has been chosen as the material for the forming process goes through initial processing by means of a laser. A 2D diagram of the pattern to be etched is fed to a laser. This is done to etch the Miura-ori pattern to be folded (see Fig. 2).

The pattern is etched in particular sequence, so that the first column is completed before the laser moves on to the next column. A set of rollers is used to move the polycarbonate sheet after the completion of a single etching process of the 2D pattern. Stepper motors are used for precise control of the rollers. A 3-Phase stepper motor having a phase change angle of 0.2 is to be used to maintain tight control.

6.2. Forming of the Etched Sheet

The etched sheet is fed to the forming section which includes 3 sets of pairs of male and female dies. The dies have indents for the Miura-Ori pattern to be formed.

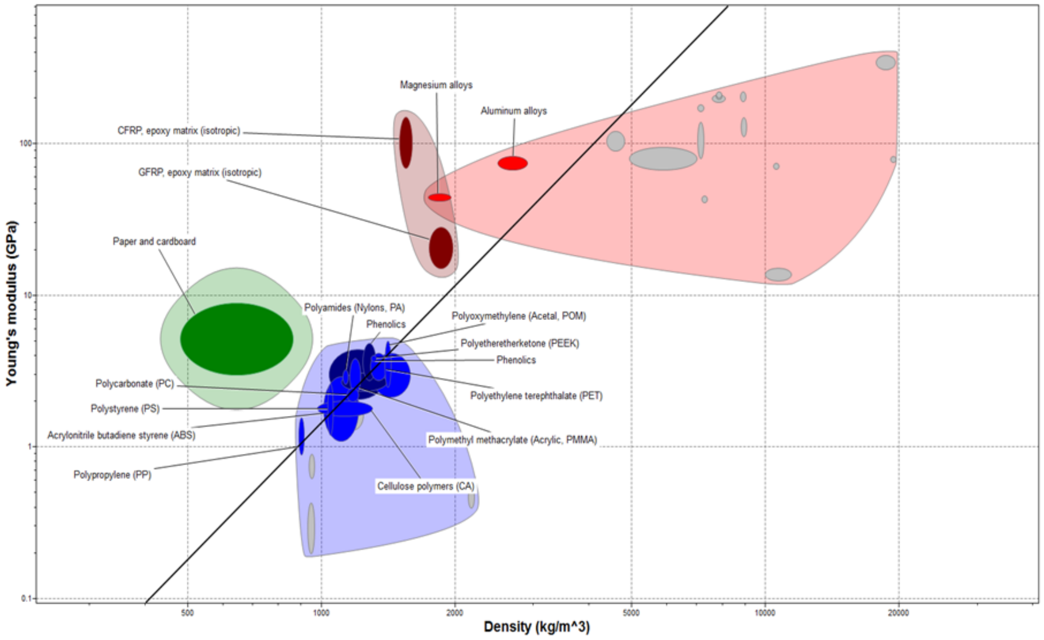

Figure 3. Map of suitable materials plotted in the coordinates of Young's modulus (GPa) vs. density (kg/m^3).

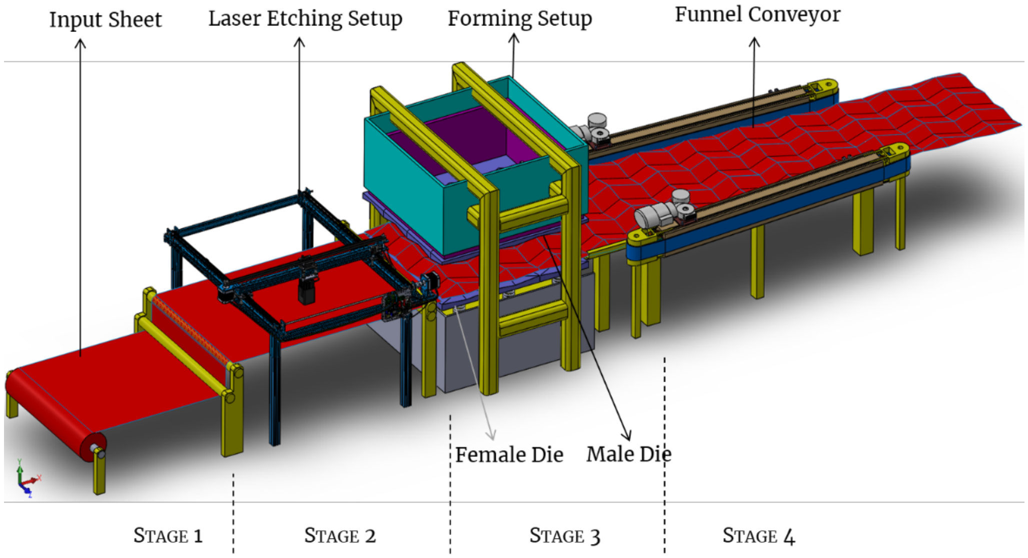

Figure 4. Layout of the Continuous Folding Machine

The dimensions of the die are based on the width of the polycarbonate roll The forming is completed in three consecutive steps, where each sheet segment is subjected to a progressive die.

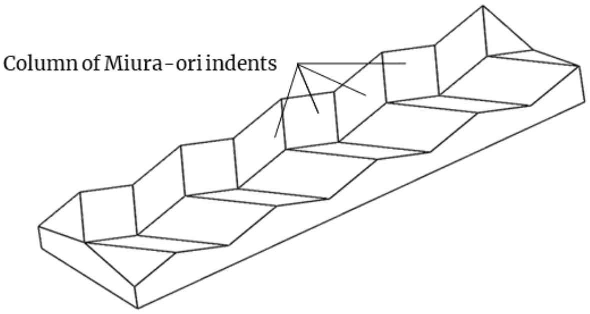

Figure 5. Cast iron pattern die

6.3. Transverse Sheet Forming

After the initial fold has been imposed on the sheet, further folding is forced by the funnel-shaped conveyer. A segment of the formed sheet is fed through a mechanical conveyor with inclined sides at an angle of 3 degrees with respect to its central axis, which are forming a funnel. The conveyor is in place for a length of 0.88 m. The conveyor setup is a fully enclosed Aluminum shell with the conveyer belts inclined at the sides. It has two functions:

- The major purpose is to ensure that the formed sheet which is in its semi-rigid state is further compressed by the conveyor system until the pattern is formed to its required final state.
- The secondary purpose is to push the formed sheet to the output stage.

The conveyer configuration forces with reduction of the folded sheet by ~16%, which also results in the increase of its height; to achieve it, the motors and rollers of the system have to be synchronized.

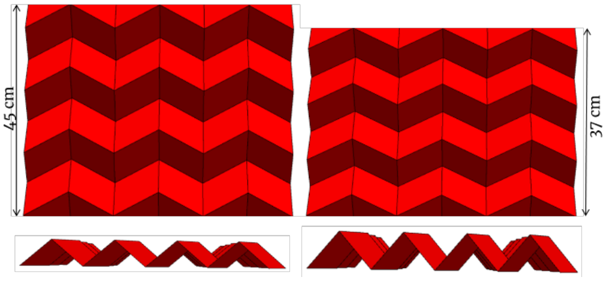

Figure 6. 3-D deformation of the folded sheet by conveyer.

7. Simulation of the Sheet Forming

In conceptual development, numerical simulations are an established tool for initial feasibility assessment. For that purpose finite element (FE) models of the composite foldcore sandwich structures were developed in the FE software Abaqus and Solidworks Simulation, and used to study the deformation of specimens under the different conditions.

The patterned sheet model was first built in SolidWorks by tiling identical Miura-ori units (Fig. 7).

Such a patterned sheet was then meshed and modeled with shell elements of type S4R in Abaqus. A material constitutive relation was used. The simulation is carried out for the final stage of the forming process in the funnel type conveyor region. The top and bottom contact points of the patterned sheet were both constrained along the Z-axis while allowing free movement in the other two axes. One of the sides parallel to the creases in the model is fully fixed while the other two sides perpendicular to the fixed side are used as load points (load applied was 50N). Self-contact was defined, which took into account hard contact and friction between the surfaces and the patterned sheet.

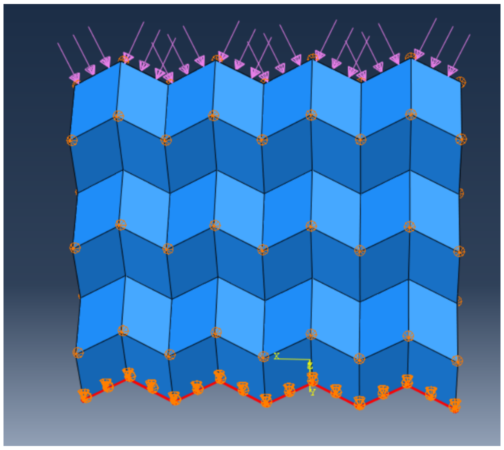

Figure 7. Boundary Conditions of a Sheet

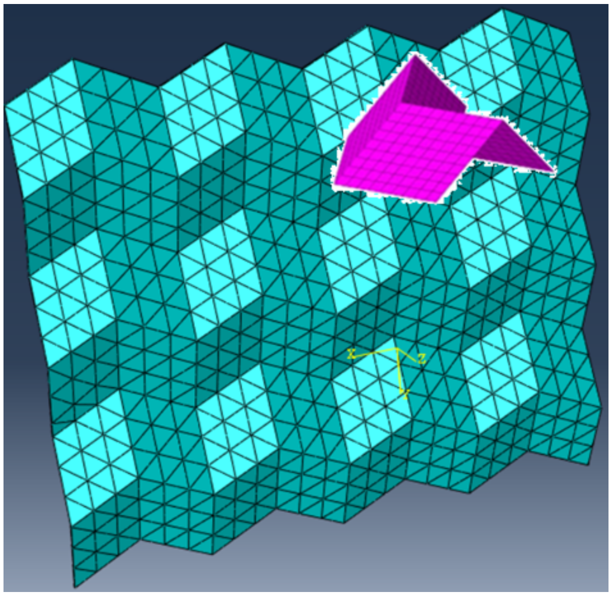

Figure 8. FE Single fold cell model and final mesh model.

The loading rate in the simulation is exerted incrementally, in steps of 5N. Therefore, a compression force of 20, 25, 30 N was applied, respectively. The force value seems insensitive to the loading rates over a range of displacement, though a speed of 20 N gave the lowest value of the force.

8. Simulation Results

The PC sheet is subjected to a load of 30 N along its horizontal sides. The deformation that occurs was found to be in line with the desired values. A compression of 6mm in overall height of the formed pattern is observed with a corresponding increase in width of the pattern.

A load of 25 N is applied on the horizontal side with the focus on compression of the tessellated sheet. The side of the sheet in contact with the roller is fixed. The points of the creases on both sides of the sheet are given free range of motion with respect to the central axis of the sheet. This allows compression along the crease patterns and forming of the required textured sheets. The Von Mises stress was used to determine if a given material will yield or fracture.

Figure 9 shows that the value of stress is within safe limits and there is no deformation to the point of shearing for this load value. The maximum principal stress shows the point of failure is more along the crease lines in the upper sections of the tessellated sheet.

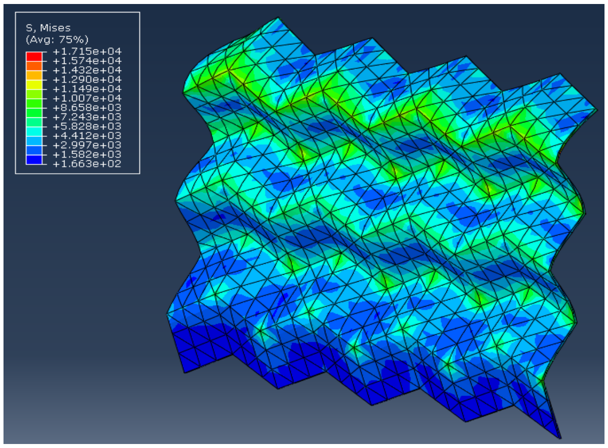

Figure 9. Von Mises stress of the tesselated sheet.

Various limitations of the layout have been identified and are listed below:

- The primary motion of the PC sheet is driven by the rollers and may cause sheet wrinkling.
- The laser etching of the crease pattern is the most time-consuming stage of the process.
- During initial setup of the machine, the die does not start forming until the sheet is in contact with the conveyer so that there is sufficient pressure holding the sheet along both directions.
- All the motors have to be precisely synchronized with the sheet flow so sheet etching matches the die indents.
- The first column of the formed pattern which enters the funnel shaped conveyor, should be properly formed so that all the following columns are formed accurately.

9. Summary and Future Work

The main objective of this simulation was to show a new approach for the production of textured sheets. The various parameters that govern the folding process are clearly defined. The results from the simulation confirm the feasibility of the proposed method. The opportunities of various failure modes were elaborated and plausible means to eliminate such limitations were provided.

The limitation of this research being fully and exclusively numerical can be addressed in the future. Further work would need to validate the presented model with additional data or a physical prototype. The approach used is framed upon ideal work conditions. The scope of proposed future work should include:

- A scaled down prototype can be built to evaluate crucial aspects of the model
- The time taken for the production can be calculated with accuracy in the case of prototype.
- A variety of different materials can be tested should define the ranges of feasible parameters of the production process.

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