FOLDING STRUCTURES: DEVELOPING A NEW METHOD USING THE PRINCIPLES OF ORIGAMI AND CNC MILLING.

Sjoerd L. van Greevenbroek
Faculty of Architecture & the Built Environment, Delft University of Technology
Julianalaan 134, 2628BL Delft
slvangreevenbroek@gmail.com

ABSTRACT

This paper aims to propose an approach for developing and manufacturing three-dimensional structures by folding of flat, thin- walled elements provided with a crease pattern, by integrating geometric, technological and structural aspects. A new foldable system has been developed, presenting an innovative configuration inspired by the principles of origami. The framework for an innovative composite material in combination with CNC milling is presented with the core advantage to provide a hinge function within the material itself.

KEYWORDS: *Origami, Folding Structures, CNC milling.*

I. INTRODUCTION

Origami, the art of folding paper with roots in ancient China and Japan, is a combination of the Japanese words “oru” (fold) and “kami” (paper) (Buisson, 1990, cited in Lebée, 2015, p. 55). Origami is directly linked to mathematics, as the length of any line drawn on a sheet will remain constant even though it transforms into many different shapes. Origami mathematics is a recent theoretical field of research, established in order to investigate the many questions in origami mathematics such as flat foldability and continuous rigid foldability. Folding paper was used by Joseph Albers in the preparation class of the Bauhaus, to help his students research the relationship between materiality, geometry and structure (Albers, 1952, p. 114-121, cited in Lebée, 2015, p. 56). Today the principles of origami are used to investigate possible translations into technological applications. These innovations combining the mathematical, kinematic or structural properties of folds are referred to as Origamics (Steward, 2007, p. 419). Implementations of origamics can be found in the fields of civil engineering, architecture, biotechnology, medicine, space engineering and other technical applications (Nishiyama, 2012, p. 269-279; Sekularac, 2012, p. 1-16; Schenk, 2011; Sorguc, 2009, p. 235-247; cited in Gilewski, Pelczynski, Stawardz, 2014, p. 221).

There are many advantages to start from a flat sheet of material, the process of folding allows you to quickly achieve three dimensional shapes with enhanced structural properties which directly defines an envelope, separating in- and outside (Peraza-Hernandez, 2014, cited in Lebée, 2015, p. 55). The kinematic properties of folds make them extremely versatile and very suitable for implementation on deployable structures. Deployable structures have the capacity to transform and adapt to multiple predetermined configurations and offer benefits when considering ease of transportation, erection and material efficiency (Fenci, Currie, 2017, p. 112 –130). From a mechanical point of view, Origami can be defined as a folded structure (Buri, Weinand, 2008; Duresseix, 2012, cited in Gilewski, Pelczynski, Stawardz, 2014, p. 221). Schenk and Guest (2011) describe foldable plates as triangular or quadrilateral panels connected to each other along their edges by means of cylindrical hinges, which allow for a deployment mechanism following an Origami pattern. Although this model has potential, the translation from foldable principle to building structure is rarely realized due to technological issues. One difficulty is the thickness of the panels and its material. Also, in order to develop a deployable structure, efficient hinges are required to be used as folds. This is where this research aims to add value. By using the principles of origami in combination with CNC milling, a deployable structure is created. The hinge is within the material itself and thus keeps the mechanism as a whole. By using a combination of parametric graphical tools and the closely intertwined fabrication process of CNC milling, it is easy to test the feasibility of a design thanks to rapid prototyping. The digital model is directly compatible with the full scale fabrication process. This research offers a new construction paradigm providing a new geometrical freedom close to the manufacturing process.

A number of studies investigated the specific applications of folding techniques in building design (Stavric, Wiltsche, 2014; Lebée, 2015; Shen, Nagai, 2017). Others have studied the development of deployable structures using folding techniques (De Temmerman et al., 2007; Chudoba et al., 2013; Heatherwick Studio, 2004; Buri, Weinand, 2008; Curletto, Gambarotta, 2015). A notable research was the research of Curletto and Gambarotta (2015), who proposed a novel and efficient approach to realize mobile structures easily transportable and assembled on site, using the potentiality of the lightweight material Hylite®, an aluminum composite panel with a polypropylene core and aluminum outer skins, with the possibility to use the core layer as hinge. Within the paper the development and manufacturing principles of a deployable structure are presented starting from an hypothesis. The basic principle of this hypothesis, the folding and manufacturing of a sheet material can be seen in figure 1, 2 and 3.

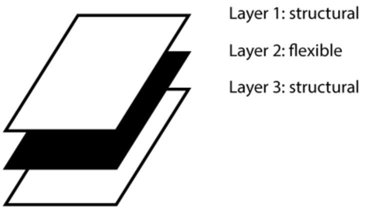

Figure 1. Build-up of composite material (Own image)

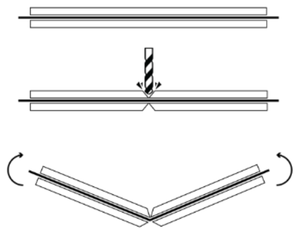

Figure 2. Manufacturing and folding principle (Own image)

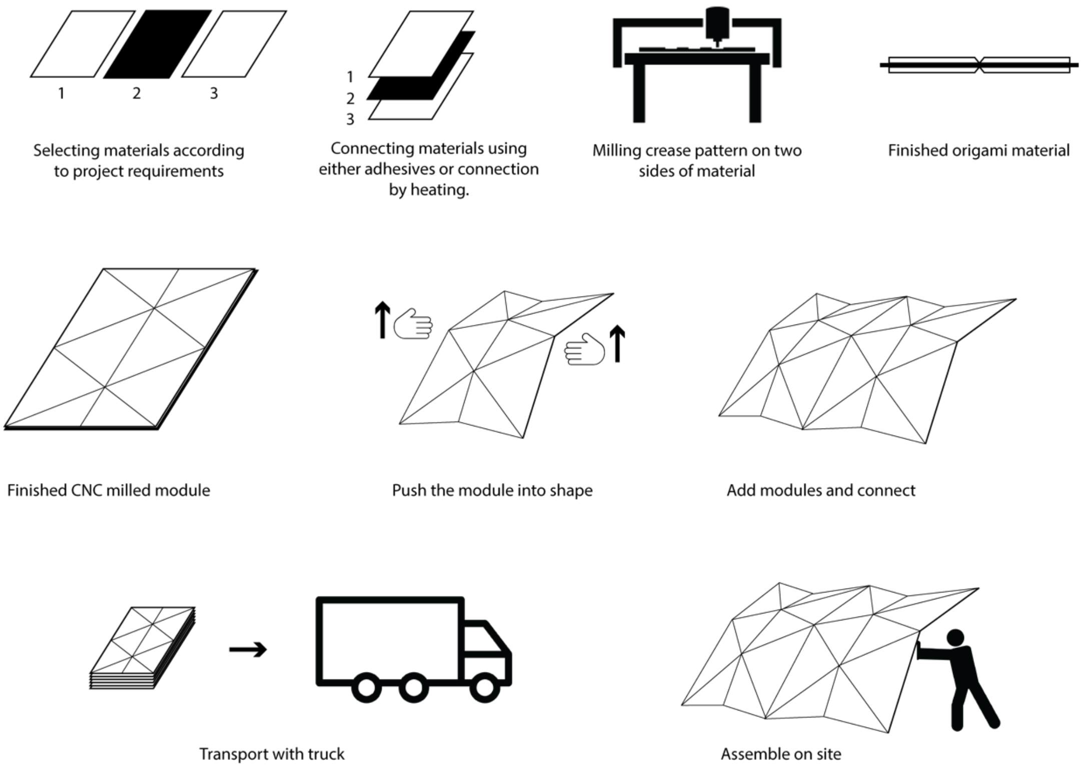

Figure 3. Manufacturing and assembly of folding structure (Own image).

A composite material is created consisting of two structural outer layers and an inner flexible layer. The two outer layers provide for the structural capacity of the module, whilst the inner flexible layer provides for the possibility of folding when exposed. Material from the structural outer layers will be cut away using a CNC milling machine, exposing the flexible inner layer. During the folding process, the exposed flexible material along the crease acts as a hinge. Using different crease patterns in the composite material will result in different shapes and expressions, whilst keeping the system as one whole. This research is based on the development of a deployable structure through the creation and use of an innovative composite material in combination with CNC milling and the principles of origami, that provides a hinge function whilst keeping the system as one whole, obtaining a lightweight system. The aim of this paper is to realize a lightweight, small scale foldable system, which is easily transportable, deployable and assembled by two persons and allows for easy reproduction and modularity of the elements to allow for larger structures, up to a span of 5m. This paper aims to propose an approach for developing and manufacturing three-dimensional structures by folding of flat, thin-walled elements provided with a crease pattern, by integrating geometric, technological and structural aspects. The goal of the first part of the research is to identify interesting folding patterns that have the potential to be translated into folded plate structures using the proposed composite material in combination with CNC milling. Also methods for the flat-foldability of those structures and methods for dealing with material thickness are described. The second part of the research aims for an analytic understanding of the chosen geometries using computer aided design. This method allows creating a large number of various forms which can adapt to specific project conditions within a short time frame. Finally, the production process of the proposed structure and a range of possible materials and limitations are presented.

II. FOLDING PATTERN AND GEOMETRY

2.1. Folding techniques

Rigid origami is a kinematic model of folding a crease pattern C, into a 3D shape such that the faces of C remain flat and the edges of C, also called the creases, act like hinges (Hull, Tachi, 2017). All deformation is focused in the hinges and the faces between the folds remain flat (Lebée, 2015). The number of kinematic degrees of freedom remains finite. Starting from a flat configuration, two directions of rotation along a fold line are possible called either mountain or valley folds (Figure 4). An alteration of these folds is possible with the reverse fold (Engel, 1989, cited in Buri, Weinand, 2008). With this technique, a single parallel fold can be bent by a diagonal crease across the parallel fold, resulting in the bending and reversing from mountain to valley fold of the original straight parallel fold (Figure 4).

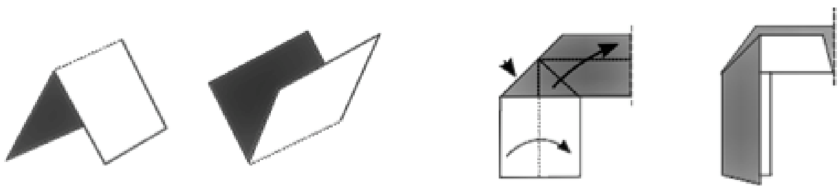

Figure 4. Folding techniques: ‘mountain fold’, ‘valley fold’, ‘reverse fold’; (Gilewski, Pelczynski, Stawarz, 2014).

The number of fold lines intersecting on a vertex determine whether rigid foldability is possible and therefore if the faces remain rigid solid. If less than four fold lines intersect at a vertex, it is not possible to fold around the vertex without bending one or more faces (Lechenault, Adda-Bedia, 2015, cited in Lebée, 2015, p. 58). With four intersecting lines and all angles smaller than π, there is one rigid degree of freedom (Huffman, 1976; Miura, 1994, cited in Lebée, 2015, p. 58). Some families of rigid origami crease patterns exhibit 1- degree of freedom (DOF) mechanisms and can be flat-folded. One is made with a network of degree-4 vertices whose sector angles are supplementary to each other, also called flat-foldable vertices and has some interesting and useful characteristics. The structure has two flat states, either flat-unfolded or flat-folded and there is a continuous path between these states, as can be seen in figure 5 (Hull, Tachi, 2017, p. 1).

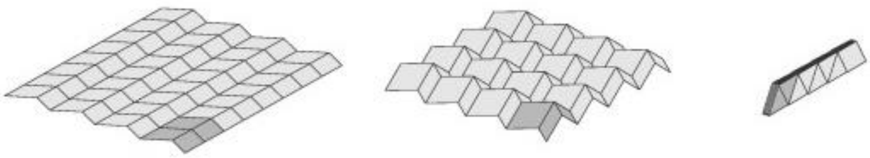

Figure 5. Flat-folding of Miura-ori pattern (Schenk, Guest, McShane, 2014).

The tangent of half of each fold angle at the creases are proportional to each other. Not all rigid foldable crease patterns are flat-foldable, therefore Hull and Tachi (2017) developed a method called double-line rigid origami to guarantee flat-foldability, even when the original crease pattern is not (Figure 6).

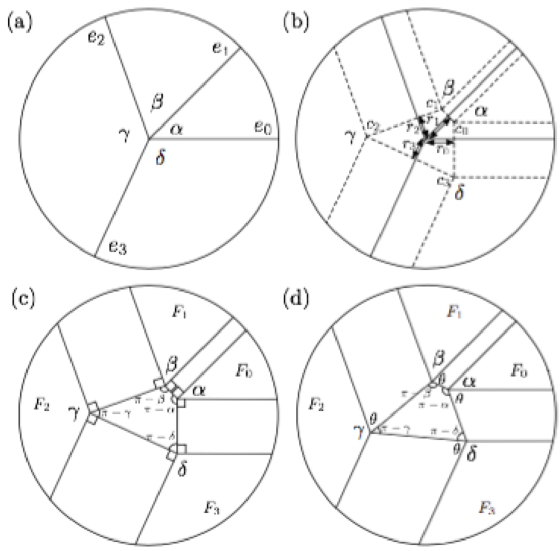

Figure 6. Double-line method: (a) Original origami vertex V. (b) Constructing polygon P and double lines. (c) New crease pattern DL(V). (d) Rotated double-line crease pattern DL(V,0) (Hull, Tachi, 2017).

The original crease pattern V (Figure 6, a) is converted into a flat-foldable crease pattern DL(V) (Figure 6, c), named the double-line version of V, consisting only of degree-4 vertices and whose rigid origami kinematics is identical to that of V. This method can interpret the kinematics of some higher degree or non flat-foldable origami as the combination of degree-4, flat-foldable vertices, so that it can help designers of rigid origami mechanisms to bring the advantages of degree-4, flat-foldable origami to more complicated crease patterns. Another benefit of the double-line method of Hull and Tachi (2017) is that it is a method for dealing with thickness. When realizing deployable structures using rigid foldable origami, the thickness of the panel is an important issue. Even the smallest modification to the position of creases can result in loosing rigid foldability. Several methods for thick panel origami have been proposed (Chen, Peng, You, 2015; Hoberman, 1988; Ku, Demaine, 2016; Tachi, 2011, cited in Hull, Tachi, 2017, p. 10) however, the drawback is that it often suffers from the trade-off between thickness and the maximum sharpness of fold angles. It is for example not possible to completely flat fold the panels because that would make the thickness of panels approach 0. The double-line method of Hull and Tachi (2017) is an effective method for volume-trim based thick rigid origami as the double-line method can split a shaper crease into multiple milder creases (Figure 7, 3). A “flat folded” state can be realized in a macroscopic sense, with the use of milder fold angles.

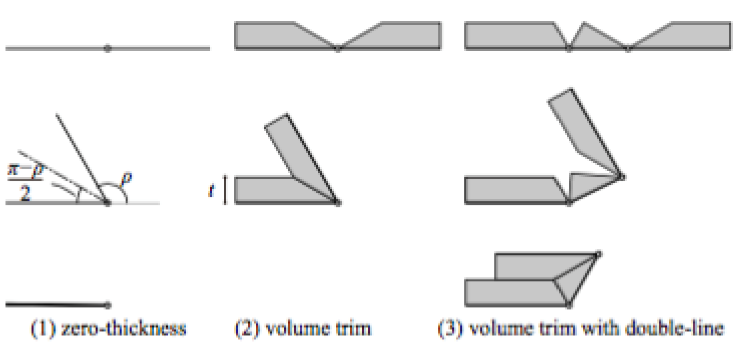

Figure 7. Thickening of double-lined origami. (1) Ideal zero-thickness origami. (2) Volume trim method applied to the original crease pattern. (3) Volume trim method applied to double-lined origami (Hull, Tachi, 2017).

A similar approach is proposed by Ku and Demaine (2016) to thicken rigid origami, however holes need to be added to each vertex which is structurally undesirable. The double-line method of Hull and Tachi (2017) can fill the hole, therefore maintaining a watertight surface that follows an analytically describable kinematics. Not every crease pattern is suitable for double-line rigid origami. However, some origami tessellations with symmetry, such as Miura-Ori and (elongated) Yoshimura-pattern can have double-line version with rigid foldability.

2.2. Folding pattern

Different Origami patterns have been investigated, including the possibility to integrate two or more different patterns. The form-finding process inspired by folding techniques gives a surprising richness and variability (Buri, Weinand, 2008, p. 2-5). Origami patterns which are particularly interesting for architectural form design, structural applications and therefore keeping rigid folding in mind, are the Yoshimura pattern, Miura-Ori pattern, Waterbomb, Diagonal pattern and Ron Resch.

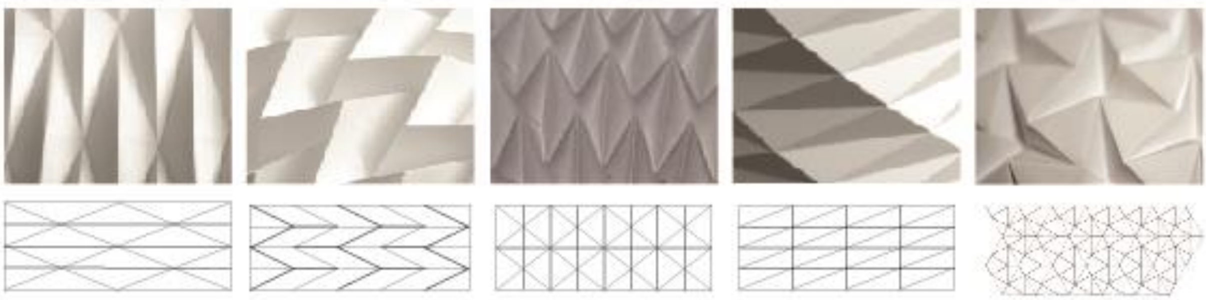

Figure 8. Origami patterns: left to right, Yoshimura, Miura-Ori, Waterbomb, Diagonal, Ron Resch.

These forms allow for rapidly complex folded plate structures and are based on a combination of simple accordion folding and reverse folds. Miura-Ori and Waterbomb base have deployment in all directions and the Yoshimura enables translational motion. Miura-Ori has been widely applied in Engineering, whilst the Waterbomb base is suitable for smart materials and more complicated designs. This consideration demonstrates that the choice of the pattern is the first point for realizing an efficient model. The original flat surface is only developable after micro-structuring it with a periodic pattern in order to generate new geometries (Seffen, 2012, cited in Lebée, 2015, p. 62). These created surfaces may be seen as “meta- surfaces” in reference to meta-materials which exhibits non-conventional global properties thanks to a finely tuned micro-structure (Schenk, Guest, 2013; Wei, et al., 2013; You, 2014; Lv, et al., 2014; Silverberg, et al., 2014; Silverberg, et al., 2015, cited in Lebée, 2015, p. 62).
Miura-Ori (Figure 8) is the most investigated pattern and can be obtained by a repetition of reverse folds resulting in the characteristic zigzag corrugation, or herringbone tessellation, in two directions. Therefore, extending and retracting is enabled in both directions. In general the zigzag line of the main fold follows a curve. Miura (1989, cited in Buri, Weinand, 2008, p. 2-5) used this capacity to build very compactly packed solar sails for satellites that could unfold to a maximum extension. Since the rigid

Miura-Ori is a 1 DOF mechanism, it is enough to lock the latter to get a structure by locking one hinge or fixing two distant points. It is one key of the success of this pattern in engineering. Ron Resch also contributed to the investigation of many new patterns (Resch, Christiansen, 1970; Resch, 1968; Resch, 1973, cited in Lebée, 2015, p. 62) His most famous tesselation (Figure 8) is characterized by large deformations with both positive and negative double curvature, as a result from his original intention to use this pattern as a structural system (Resch, 1968, cited in Lebée, 2015, p. 62). Japanese scientist Yoshimura observed that thin walled cylinders show a buckling pattern under axial compression (Hunt, Airo, 2005, cited in Buri, Weinand, 2008, p. 2-5). This buckling pattern forms the basis for the Yoshimura Pattern (Figure 8), which consists of a diamond shape fold in one of its diagonals. When distorting the diamond into a kite shape the inflection of the curve changes, allowing it to approximate any continuous curve (circle segment, parabola, etc.). The Yoshimura- and diagonal- pattern have many similarities, the main difference is the fact that valley folds of a diamond pattern form a plane polygonal line whereas the valley folds of the diamond pattern form a helical polygonal line. The distance between the centreline and the edge lines marks the amplitude of the folds. De Temmerman et al. (2007), proposed an alteration of a folding pattern by changing the apex angle of only the outer most modules to $\pi/2$, resulting in increased compactness compared increased inner space. This alteration, however, makes it structurally less efficient.

III. PARAMETRIZATION

As the relationship between crease pattern and the resulting shape is only obvious in simple cases, a support by numerical simulation in all phases of design and production is required in order to have a correct interpretation of its complex behavior. Modifications of crease patterns, folding angles or segmentation such as the proposed alteration of De Temmerman et al. (2007), have a large influence on the flexibility of the shapes and therefore also on the load-bearing behavior. These modifications can also be used as an advantage, for example for structural optimization (van der Woerd et al. 2013). By using a parametric modeling tool such as Grasshopper (Rutten, no date, cited by Curletto, Gambarotta, 2016), a valid and reproducible Origami foldable structure can be made. The software can be used to draw and edit complex models and simultaneously extract updated data analysis, by changing geometric, technological and structural parameters and their relationship. All geometric parameters that characterize the dimensions of the model and their relation have to be identified. Then the geometry has to be converted into a structure, mechanical data has to be assigned, and the structural response can be obtained using FEA. Another example is the use of the modeling framework Oricreate which has been developed and implemented by Chudoba et al. (2013); Chudoba, van der Woerd and Hegger (2015) for their creation Oricrete. The platform can be used for three types of applications: form-finding, including adaption and optimization of crease patterns to achieve desired shapes and improve the load-carrying behavior, simulation of the folding process, and structural analysis and characterization of mechanical properties of the folded structure.

IV. STRUCTURAL ANALYSIS

When designing a foldable structure, understanding its structural behavior is required in order to find the best configuration of deployment. Computational methods can strongly contribute to this aim, allowing drawing and modifying complex models and simultaneous carrying out the structural analysis, as described by Curletto and Gambarotta (2016). In their research, the parametric software Grasshopper and its plug-in Geometry-Gym have been applied to define both geometric and structural data which is then loaded into the finite element analysis package Ansys. Starting from the concept of rigid folding, with rigid facets, straight fold lines and perfect hinges, only relative rotation is allowed along fold lines. Bending moments are the critical stress resultants transferred between adjacent plates, therefore the structural behavior of the system and its overall stiffness depends on the capacity of the crease to resist bending moments (Figure 9). A mechanical model to calculate these stresses, is to assume that it is an assembly of shells connected through elastic hinges. This common way of modeling allows for finite element computations. Stresses are described as: membrane stress N, bending moment M and the shear force Q, which give a good description of the actual solicitations in the faces. Deformations in folding structures are mainly focused in the folds, as illustrated in the investigation of Hassis and Weinand (2007, cited in Lebée, 2015, p. 64) where a generalization of Miura-Ori was directly built with rather thick wood plates. It shows that the failure mechanism is completely focused in the hinges and the wood itself is loaded below its actual strength. Therefore, improving the connection strength is a necessity. However, the observation points out a limitation to structures derived from folds: either, the structure is thin, light and cannot sustain large loads, or it fails in the folds when using stronger and heavier materials. This illustrates the importance of the search and selection of a strong yet lightweight structural material and a tear-resistant flexible layer.

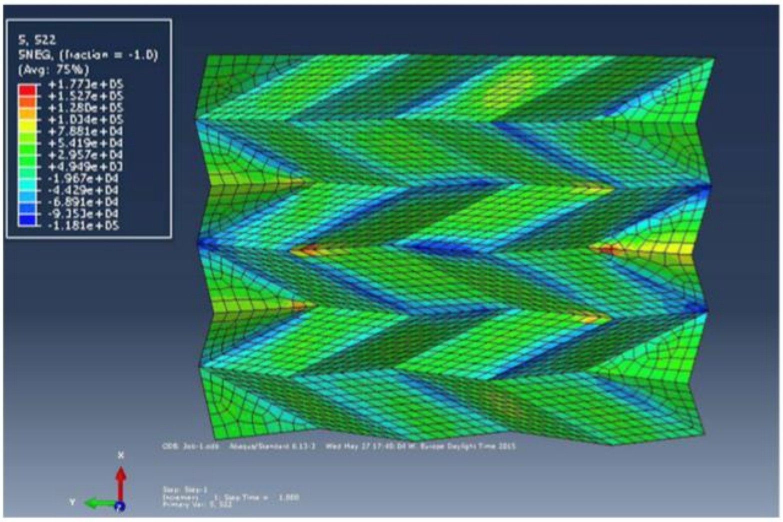

Figure 9. Typical stress distribution of Origami pattern, Miura Ori (Samuelsson, Vestlund, 2015).

The results of various investigations regarding the structural behaviour of folded structures is discussed below and form a framework for structural design decisions. Gilewski, Pelczynski and Stawarz (2014) presented a paper dedicated to the analysis of folded plates inspired by origami. Various origami patterns were compared according to their maximum displacements and stresses. The best results were obtained for the longitudinal pattern and promising results were obtained for the Miura-Ori pattern, illustrating why one, or both of these patterns have been chosen for several folding structures (Curletto, Gambarotta, 2016; Buri, Weinand, 2008; De Temmerman et al. 2007). Van der Woerd, Chudoba and Hegger (2015) describe an optimization of the structure through experimental investigations with different angles, resulting in different load-carrying capacities. Generally speaking sharper angles result in higher load-carrying capacities. In a subsequent research, Van der Woerd et al. (2014) show a parametric study of a folded and segmented dome, with the comparison of the principle moments for 20, 40 and 60 segments. The maximum deflection for the applied vertical load was calculated in order to compare the stiffness properties of the three studied segmentations, resulting in the conclusion that the larger number of segments leads to a stiffer structure with lower bending moments. By adding multiple segments, the stresses are divided over these increased number of segments, leading to lower bending moments per segment. This consideration can help develop a structure with lower stresses in the creases and therefore can improve the feasibility of the system. Buri and Weinand (2008) describe a static load test, showing important deformations of the structure particularly on the open sides. The results showed the importance of the connections in the proposed structures. In their load-bearing test, all failure was focused on the creases. These results and considerations will be used as guidelines for the design of a folding structure.

V. Proposal of Process

Despite the wide research and broad diversity on foldable shapes, applications are not very common in Architecture and Civil Engineering, due to difficulties with converting geometric models into built structures. When doing this, different parameters are considered and technological issues arise. Folding mechanisms involve complex kinematics, with simultaneous motion in all folds. Developing a manufacturing process based on folding techniques to produce the folded shape, can therefore be a difficulty. Folding continuously transforms a flat surface into 3D space, meaning a folded shape is not a structure of itself, but rather a mechanism. In order to turn a folded surface into a structure, this mechanism has to be closed. Moreover, since rigid-Origami structures have mainly been studied in

Academia, an industrial standardization for connections, joints and such doesn't exist. More important however, are issues related to the choice of material and thickness of the plates, which impede the possibility to flat fold the structure as discussed for instance in (Trautz, Kunstler, 2009; Tachi, 2009, cited in Lebée, 2015, p. 63). Multiple strategies for dealing with thick elements have been proposed, for example Tachi (2011), however the most promising method to overcome this difficulty is the earlier described double-line method of Hull and Tachi (2017). Deployable structures require lightweight materials, for ease of both transportation and manipulation and to enhance its structural properties as described earlier. Several attempts have been developed, testing different materials such as concrete, cardboard and wood, as proposed by Robeller (2015).

5.1. Material Selection

During the process of finding suitable materials for this cause, the CES material library is consulted. The outer layers are required to provide enough structural security and the inner layer is required to be flexible yet capable of resisting large stresses due to folding and loads. The inner layer is therefore the most critical layer, as large stresses will appear along the crease lines. The material choice has a large impact on the model, since it directly affects structural behavior, technological solutions and aesthetics. Possible solutions that have been proposed by several researches are: concrete (Chudoba et al., 2013), wood (Buri, Weinand, 2008), textiles (De Temmerman et al., 2007) and aluminum composites (Curletto, Gambarotta, 2016). All materials have their specific characteristics, aesthetics, properties and suitable manufacturing methods. The choice of the material for this paper is related to both technological and manufactural considerations. As the aim of this paper is to realize a lightweight, small scale foldable system, up to a span of 5m, which is easily transportable, deployable and assembled by two persons and allows for easy reproduction and modularity of the elements to allow for larger structures, multiple materials have been investigated in order to create the earlier suggested composite. As derived from the structural analysis, foldable structures require panels of a light and stiff material, so the requirements for the structural layers are a lightweight material with high dimensional stability (Burchitz et al., 2005). The material index M_b, as proposed by Ashby (1999) has to be evaluated:

$M_b = E^{1/3}/\rho$, (Ashby, 1999)

where E is the modulus of elasticity and ρ is the material density. The index M_b suggests the best material to use for a minimum weight (Boesenkool et al., 1997). The selection-line has a slope of 3.

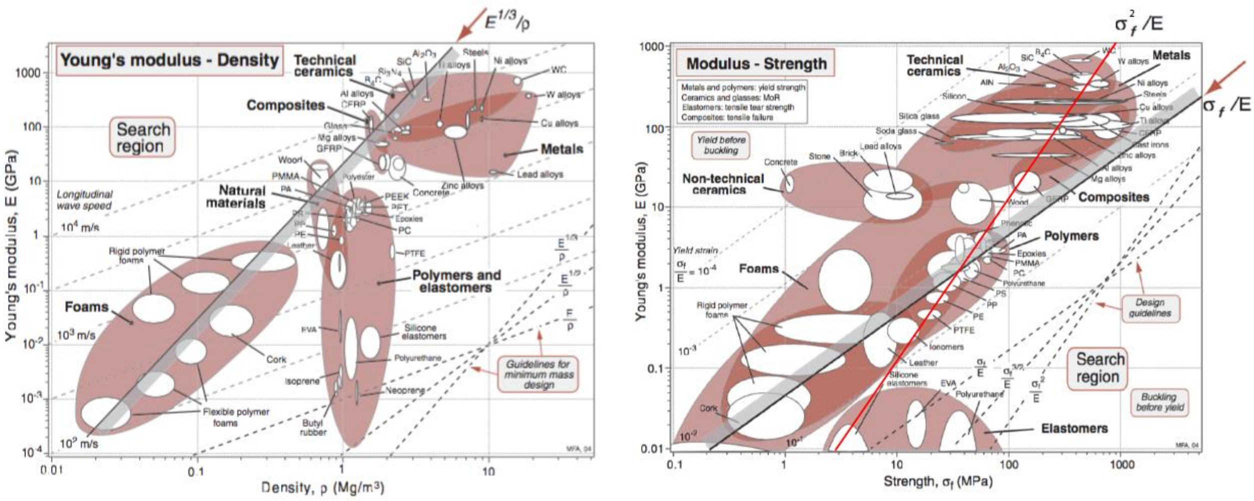

Figure 10. Material selection in CES, left: Structural material, right: elastic hinge (Ashby, 1999).

In the chart (Figure 9, left), the best materials for a minimum weight and deflection limited design lie top left. This plot shows good performance of wood, carbon-fiber and glass-fiber reinforced polymers and stiff foamed polymers.

The flexible layer has to be lightweight and able to withstand high tensile stresses. The material that can be bent to the smallest radius without yielding or failing is the ideal one to be applied as hinge. This property can be evaluated with the index M_{h}, as demonstrated by Boesenkool et al. (1997):

$M_{\mathrm{h}} = {}^{\sigma f}/_{E}$, (Ashby, 1999)

where σ_f is the failure strength. Both criteria involve ratios of σ_f and E, where σ_f will be identified with the modulus of rupture, σ_{MOR}. A chart has been created where σ_{MOR} is plotted against E (Figure 9, right). Candidates for unstressed hinges are identified by plotting M_1 as a line of slope 1, which is shown at the position $M_1 = \sigma_f / E = 0.03$. The best choices for the hinge are all polymers. The short list (Table 1) includes polyethylenes, polypropylene, nylon and, best of all, elastomers; although they may be too flexible. However, this formula is based on a situation where the hinge carries no significant axial loads. In this model the hinge is required to sustain high stresses, which sets a minimum value for the thickness, t, which is found by requiring that the tensile stress, F/tw (where w is the hinge-width) does not exceed the strength limit σf. This will result in the second index:

$M_{\mathrm{h}} = {}^{\sigma^2 f}/_{E}$, (Ashby, 1999)

The intersection of the M_1-M_2 grids gives the most suitable material for both elastic and strength, which narrows it down to polymers.

Table 1. Materials (Ashby, 1999).

Material	**M_1 (x 10^{-3})**	**M_2 (MJ/m^3)**	**Comment**
Polyethylenes	30 – 45	1.6 – 1.8	Widely used for cheap hinged bottle caps, etc
Polypropylene	30	1.6 – 1.7	Stiffer than PEs. Easily molded
Nylon	30	2 – 2.1	Stiffer than PEs. Easily molded
PTFE	35	2 – 2.1	Very durable; more expensive than PE, PP, etc.
Elastomers	100 – 300	10 – 20	Outstanding, but low modulus
Beryllium-copper	5 – 10	8 – 12	M_1 less good than polymers. Use when high stiffness required
Spring steel	5 – 10	10 – 20	M_1 less good than polymers. Use when high stiffness required

As discussed, a range of materials meet the set criteria and are therefore suitable for using in the composite material. The final choice of materials depends on extra criteria set for a certain goal of implementation or function.

5.2. Fabrication and Assembly

The choices of material per layer can be assembled into a final composite material using either thermal connection methods or adhesives. Now the material is ready for CNC milling. The CNC milling process consists of choosing different milling bits, which will result in a variety of milled slots fitting different requirements. For example, the total height of inflections of the pattern can result in larger or smaller angles along crease lines, which will result in a required distance between the edges of the structural layers in order to allow for the angle to be made without the structural layers touching each other. This requires the use of matching milling bits. An overview of different CNC milling techniques and bits can be found in Van Veen (2016). After a certain crease pattern has been CNC milled, a three-dimensional structure can be made using folding along the crease lines. In order to create structures larger than a single folding sheet module, a connection between modules has to be developed. Due to the focus on the development of a folding sheet module in all its aspects in this paper, the connection between modules falls out of this research. A possible solution has been proposed by Curletto and

Gambarotta (2016), where three panels of Hylite® compose the base module of the structure through a bolting connection. The same bolting connection is used to connect multiple base modules together in order to allow for larger structures.

VI. CONCLUSIONS

The presented paper is dedicated to the development of a framework for the production method for origami inspired folding structures using CNC milling. Structure and envelope are achieved with a single material and technique. The principles of origami and their connection with architectural structures have been presented. By considering the proposed technique as starting point for a form-finding process, inspiration for both architectural structure and form design is given. The presented examples in literature have contributed to the recognition of origami as an "engineering discipline" allowing trans-discipliner studies and showing the possibilities for the use of such principles and their features in the field of architecture. Origami and it is potentials have been explored in computational design, allowing for the integration of computational manufacturing in the process. The use of origami allows for rapidly complex folded plate structures with a great variety of forms and possible flat-foldability. A short review of folding techniques has been given in order to provide the basis for the selection of a fitting crease pattern for the folding structure. The Miura-Ori has promising results for the use in folded plate structures. And the double-line method of Hull and Tachi (2017) can deal with thick plates and flat-foldability whilst maintaining a watertight surface. The necessity of the use of parametric tools like Grasshopper and it's plug-ins has been explained as it is interconnected with the form-finding process, the structural analysis of the design, the development of small scale prototypes and later the development of final full scale models. By reviewing the development and analysis of multiple proposed folding structures by, a framework for considerations in structural design is proposed. A framework for the selection of the different layers of the composite material has been presented, leading to a range of possible materials. Final project specific criteria will lead to the selection of the best suited material for its specific purpose. There is great potential for the design and creation of structures made by folding. The design concept of the proposed principle can also be applied to other free formed surfaces. The manufacturing concept opens up new fields of application in folding structures and CNC milling.

This paper aims to propose an approach for developing and manufacturing three-dimensional structures by folding of flat, thin- walled elements provided with a crease pattern, by integrating geometric, technological and structural aspects. A new foldable system has been developed, presenting an innovative configuration inspired by the principles of origami. The framework for an innovative composite material in combination with CNC milling is presented with the core advantage to provide a hinge function within the material itself. A prototype of the proposed system is to be produced, remaining object of discussion for future works.

VII. LIMITATIONS AND LOOKOUT

In this paper, a construction method has been proposed. The next step to develop the method, is to create small scale models in order to demonstrate the feasibility of folding structures using CNC milling and the principles of origami by comparing the deformation of the prototype with a numerical model. For further development of the method, an increase in scale is needed by means of an experimental proof of concept, investigating the feasibility of the method for larger structures. In order to create structures larger than a single folding sheet module, a connection between modules has to be developed, preferably connections using the capabilities of the material and CNC milling without additives. These next steps will give a range of limitations for the implementation and scale of the proposed folding structure. The presented framework will be used in the development of deployable structures, which introduce a novel and unique type of engineering, allowing structures to be compactly packaged and expanded when needed. Whilst retaining the functionality of traditional structures, they are able to undergo large configuration variations in a controlled and autonomous manner. The principles of origami can play an important role in design stimuli in the early stage of architecture design process and as all steps are retraceable. Also, the application of unfolding techniques for architecture design, or the reverse process of folding, opens a wide perspective for developing folding techniques. Its load-bearing behavior and limitations will be tested and simulated in the following step. A challenge in the development of this construction method remains the design of the connection between modules in order to create larger structures then only one sheet of material. The resulting structures can be used not only as load-bearing structures, but also for façade systems or shells.

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