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Origami–Inspired Structure According to Pattern, Manufacturing and Application: A Review

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ABSTRACT

Corrugations can be one of several methods to enhance the properties of thin-walled mechanical structures. It is considered a solution to many application problems for devices and equipment and to solve engineering problems. This paper highlights the most famous origami shapes, manufacturing methods, and applications. The shapes of origami are dependent on the degree of freedom. This means that the shapes in this paper discussed the five most common types and the cell units they consist of. All shapes were drawn up with all their details. The common patterns were waterbomb, Miura-Ori, Yoshimura, Kresling, and Resch. Owing to the ability of energy absorption and mechanical features, Miura-Ori was deeply discussed. For manufacturing processes, the most known methods were highlighted, which gave a hint for manufacturing differences in origami. The applications of origami in seven fields were presented in detail. The seven fields were automotive, aeroplan, aerospace, buildings and structures, biomedical engineering, map and floor plan, and architecture. Applications of origami in engineering have been extensively reviewed in fields such as the architecture field in the five specific disciplines. The objectives of the study are to make readers recognize the shapes of origami, to show the most important methods of manufacturing processes for origami, and to provide the applications in major origami-based engineering fields. In conclusion, this paper provides a significant reference for those interested in this matter or in the field of origami to obtain a wide and concise view of patterns, manufacturing processes, and applications of origami structures.

1. Introduction

Origami is defined as a word that gives an indication of an olden art for paper that is folded by hand. Origami has two origin roots. Two roots are Japanese: “ori” means “folded,” and “gami” means “paper.” Also, apanese paper folding is a traditional method for creating shaped items, such as animals. (Kanade, 1980; Liu, 2019; Xiang et al., 2020). In the early 1900s, origami gained global popularity as a recreational hobby. And recently, engineers have been more interested in using origami (Xiang et al., 2020). Origami is the art of creating a well-designed three-dimensional structure from a two-dimensional sheet. (Liu et al., 2024).

The researchers noted that the old-style folding and form geometry used in samples of paper art can be easily modified, investment in the expansion, amplification, and development of more new devices and model structures.

Because of the corrugation, the origami has two contradictory qualities; therefore, it is considered highly directional. Also, it significantly depends upon the applied force's direction (Al-Jothery & Albarody, 2025).

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Before delving into the details of origami shapes, it is necessary first to explain some common origami terms (Turner et al., 2016):
*A crease is a folding method, either convex (mountain) or concave (valley), where all the creases are folded together.
*The vertex is the point where two or more wrinkles meet.
*The number of creases emanating from the vertex is called the degree of the vertex.
*The final result of some folding movement is the folded state.
*Figure 1(a) shows a pleat that is folded by creating sequential creases to form mountains and valleys, which are adjacent and consecutive, one after the other.
*Figure 1(b) describes a crimp, which is like pleating but includes some folding in reverse in a valley and mountain shape. An example of the folds of pleats is illustrated in Figure 1(a), while Figure 1(b) depicts an example of crimp folds (Lee, 2017; Turner et al., 2016).
*Rigid origami involves connecting rigid panels with frictionless hinges to create fold patterns. The specific focus is on fold patterns characterized by fourfold lines converging at each vertex, sometimes referred to as degree-4 vertices. Each such vertex has one degree of freedom, a tessellated fold pattern is over constrained, and Folding is feasible alone under stringent geometric conditions (Nishiyama, 2012). Rigid origami has garnered the attention of scholars in mathematics and engineering. In a rigid origami configuration, the areas enclosed by crease lines are prohibited from stretching or bending during the folding process (Xiang et al., 2020). Consequently, rigid origami treats creases as hinges and characterizes the material between creases as inflexible, preventing it from bending or deforming during the folding process (Turner et al., 2016).

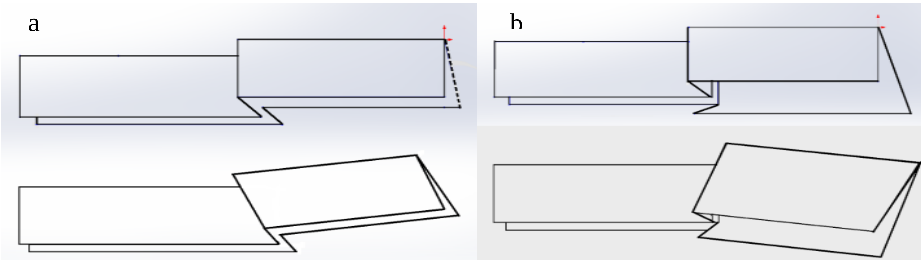

Figure 1. Material folding: (a) Pleat fold, and (b) Crimp fold

After these terms have been clarified, this paper is focused on three main subjects of origami: firstly, the shapes of origami; secondly, the manufacturing processes of origami, and thirdly, the applications of origami. Figure 2 clarifies what the review paper of origami's main subjects is.

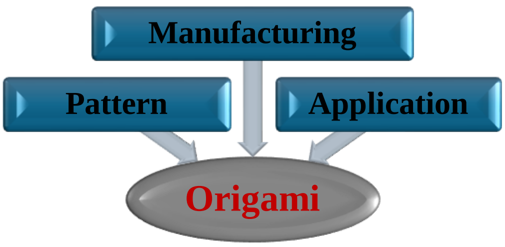

Figure 2. Main subjects of review paper

The shapes of Origami are classified into five famous shapes named after the people who invented them (Nishiyama, 2012). These different shapes play an important role. It is very important by influencing mechanical properties and strength of materials. Therefore, the automotive industry in recent years has vehicle weight without neglecting the vehicle's ability to withstand a collision (Liu et al., 2024).

There are many methods for origami manufacturing processes. These methods of Origami or corrugated sheets are dependent on materials. Some of the manufacturing processes methods are traditional(Harris & McShane, 2020). This work discusses these methods of manufacturing processes for Origami in its own section.

Applications of origami in general include several engineering fields, for example, architectural engineering (such as building facades; and interior design, such as flat-foldable furniture) and mechanical engineering (such as automotive, Aeroplan, and Aerospace (Hüseynli, 2016).

This paper is regarded as a guide for readers by explaining the review papers for previous researchers and discussing the classification of origami shapes, manufacturing processes methods and the application of origami. In addition, The article was established and written on the basis of notes taken by reading previous research and literature reviews. It was noted that there is a gap in organizing, scattering, and the lack of the classification of forms, methods of manufacturing, and applications of origami. The aim of this paper is to shorten this gap and redraw all shapes of origami with its unit cell with more details. Also, the collection of the most famous origami manufacturing processes methods is explained. In addition to that, this article presents the review of recent origami-based applications. The study's aim or objectives are as follows: (a) to make readers recognize the shapes and units' cells of Origami, (b) to show the most important and famous methods of manufacturing processes for origami, and (c) to deliver an exhaustive review of the applications across prominent Origami-based engineering focused on using one of these shapes to reduce domains. Figure 3 explaining the methodology and the structure of this review paper.

2. Origami Pattern

Origami shapes use crease patterns in many engineering applications. There are several patterns of origami shapes but, common are five patterns. These patterns are the waterbomb, Miura-Ori (Al-Jothery et al., 2020), Yoshimura, Kresling and Resch, and according to these patterns, the structures are folded. This classification is according to the dynamic load applied on the single cell unit and degree of freedom. All other shapes are classified under those five most common shapes, for example, the trapezoid, stars, honeycomb, origami 'spring' fold pattern etc. Where all other shapes after the load are applied to them will belong to those five shapes. So, these five patterns can be identified as tessellation or unit cell origami patterns, and this means that the cell of the unit has been regenerated above the whole sheet (Liu, 2019). The most popular patterns are classified into:

2.1 Yoshimura Pattern

The Yoshimura pattern resembles a diamond tessellation, which contains either the valley or the whole mountain folds alongside the diagonals. The diamond shape in the pattern is responsible for the sheet curve beyond the folding, which produces a radius of a curve or cylinder. Also, it is possible for this crease pattern to be hexagonal by adding folds that are made along the diagonals of diamonds. The translational and rotational motion is allowed in the structures that are based on the Yoshimura pattern only (Liu, 2019). Also,the valley folds in Yoshimura pattern shape are a two-dimensional polygonal line (Kresling, 2020). That means the valley folds presented dashed lines, while the mountain folds in the Yoshimura pattern presented solid lines, as revealed in Figure 4 (Xiang et al., 2020).

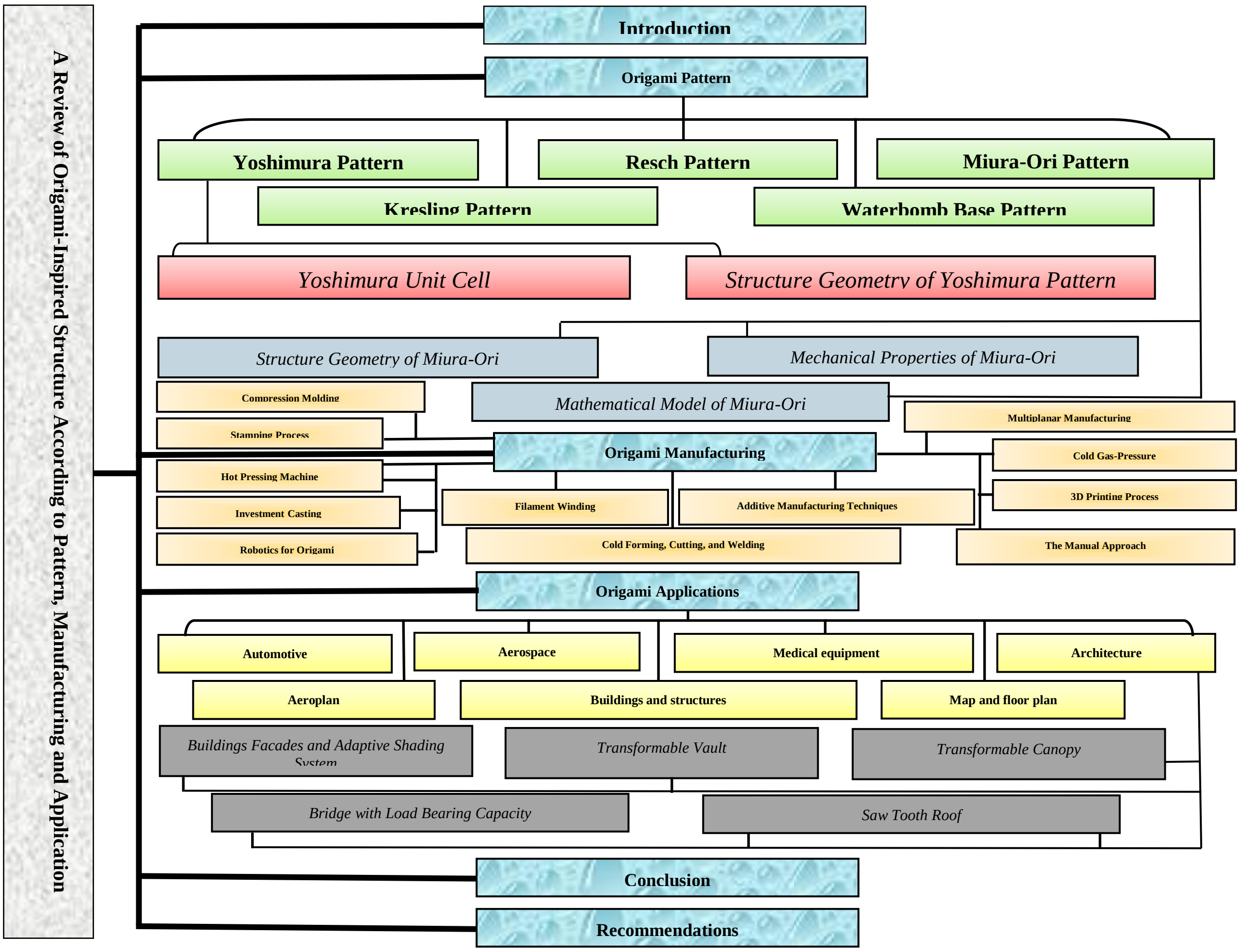

Figure 3. Structure of paper

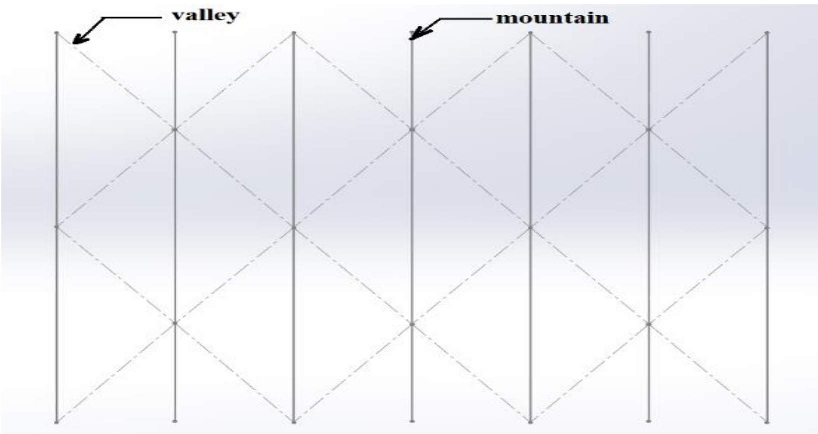

Figure 4. 2D valley folds and mountains fold of Yoshimura pattern

2.1.1Yoshimura Unit Cell

The Yoshimura pattern consists of a set of diamond tessellations (unit cells), with the valley or the whole mountain folds alongside the diagonals. The unit cell of the Yoshimura pattern comprises two components; the first part is the mountain fold, but the second part is the valley fold (Suh et al., 2021). Both are drawn and assembled by SOLIDWORKS software. Figure 5 manifests the Yoshimura pattern where (A) is the unit cell number one for the Yoshimura pattern, (B) is the unit cell number two for the Yoshimura pattern, and (C) is the Yoshimura pattern sheet.

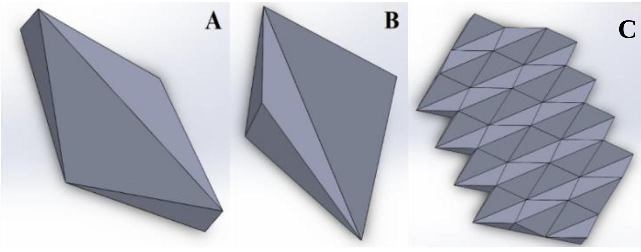

Figure 5. Yoshimura pattern. (A) unit cell number one; (B) unit cell number two, and (C) Yoshimura pattern sheet

2.1.2 Structure Geometry of Yoshimura Pattern

The structure geometry of the Yoshimura pattern plays a very important portion; this structure consists of groups of crease patterns, and these crease patterns are created from parallelograms. These parallelograms folded in a single direction alongside their diagonals as well as in conflicting directions alongside their parallels create the crease pattern (Ma et al., 2018). These lead to, for example, tunable stiffness (Fei & Sujan, 2013), negative poisson's ratio (Sareh & Guest, 2015b), tunable acoustics (Karmakar et al., 2024), improved the thermal properties, and finally, a suitable failure style when subjected to impact (Kresling, 2020; Sareh & Guest, 2015b). This leads to the capability to have higher energy absorption.

2.2 Kresling Pattern

The Kresling pattern is a twist buckling configuration observed in thin-walled cylinders (Kresling, 2020). It can be said that, it is a thin and foldable sheet of linked parallelograms throughout the mountain crease lines. By the crease lines of the valley, every parallelogram is separated into (2) similar triangles. This is called Kresling unit cell. Three ends or further parallelograms are attached, and a unit cell of Kresling is made up. A helical polygonal line made up the valley folds of a Kresling pattern shape (Kresling, 2020). There are several outstanding features of this origami pattern, such as twisting during folding and coupled axial compression, deployability, configurations of bistable, and rarefaction wave phenomena (O'Neil, 2024). The structures based on the Kresling pattern only allow for translational and rotational motions (Liu, 2019). Nevertheless, the Kresling pattern rotates as it collapses instead of contracting in a translational manner (Chia & Debnath, 2009). Finally, the Kresling was initially noticed as the ordinary reaction if torsion was exerted on the cylinder (Sareh & Guest, 2015b). Figure 6 explains the 2D valley folds and mountain folds of a Kresling pattern, where the dashed lines present the valleys of the pattern, and solid lines present the mountains of the pattern.

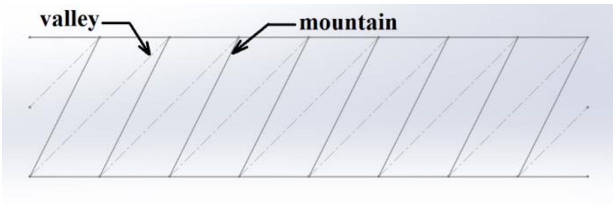

Figure 6. 2D valley folds and mountains fold of a Kresling

Figure 7 shows the Kresling pattern, where (A) is the front view of the Kresling pattern, (B) is the top view of the Kresling configuration, (C) Kresling configuration unit cell, and (D) the Kresling pattern shape.

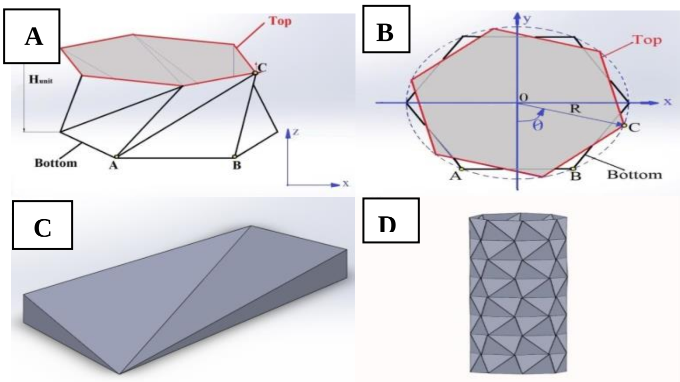

Figure 7. Kresling pattern

2.3 Resch Pattern

The crease pattern of Resch is a set of squares that bend in rotational movements along their diameters. The structures based on the Resch pattern only allow for translational and rotational motions (Liu, 2019). It has been drawn by using SOLIDWORKS software. Figure 8 shows the cell of unit and sheet folded of the Resch pattern, where (A) is the cell of unit of the sheet pattern in 3D for the Resch pattern, (B) is the front view of the unit cell in 2D for the Resch pattern, and (C) is the pattern sheet.

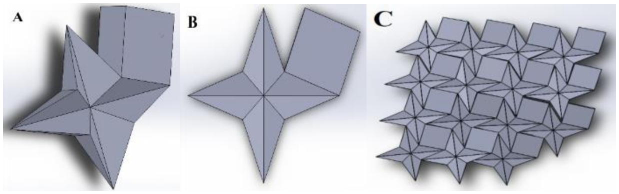

Figure 8. Resch pattern

2.4 Waterbomb Base Pattern

A waterbomb base is a classic origami sequence. The mechanism of creating it is by folding the sheet along the middle using a mountain crease and along the diagonals using valley creases to collapse the paper into a layered triangle (Hull, 2002). The waterbomb design has been utilized to create foldable cylinders, and it is considered a well-known origami pattern for this purpose. the foldable cylinders, such as stent grafts and deformable robot wheels (Ma & You, 2014). The waterbomb pattern is considered a bistable mechanism and a single vertex. It can be generalized to absorb many geometric, kinetic, and kinematic needs. The Waterbomb pattern has been redrawn by using SOLIDWORKS software as shown in Figure 9. Figure 9 explains the Waterbomb base and its unit cell, where (A) is 2D of one unit cell illustrating valley and mountain dashed lines presenting valleys and solid lines presenting mountains, (B) is the Ball of waterbomb base, and (C) is the translational motion.

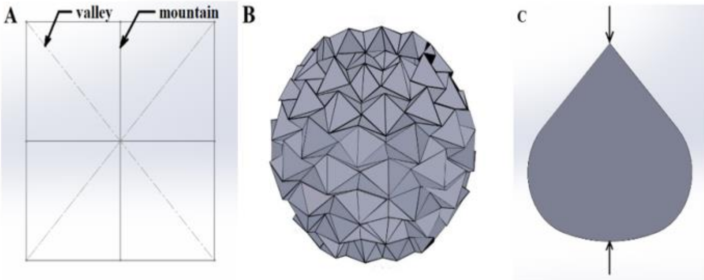

Figure 9. Waterbomb base: (A) 2D of one unit cell, (B) Ball shape of waterbomb base, (C) Translational motion

2.5 Miura-Ori Pattern

The Miura fold pattern, or the Miura-Ori origami, is a flat-foldable origami pattern with various applications in engineering and architecture (Sareh & Guest, 2015a). In 1970, Dr. Miura Koryo, a professor at the University of Tokyo and president of the Japan Origami Academic Society, invented Miura-ori. Miura-ori is a technique that allows even a large sheet of paper to open out quickly and be bestowed again by folding it on its diagonals through pulling and pushing. The Miura-ori pattern is extremely used in engineering (Lv et al., 2019). This technique was used in Japan in products like tourist guides, train route maps, and handy maps (Meloni et al., 2021). As mentioned before, the Miura-ori pattern is popular all over the world. Moreover, it reaches as far as astronautically engineering through using it in solar-panels. This technique is applied in the Japanese space program by using it in large solar panel arrays for space satellites, which it used before going to space and after spreading out (Ma et al., 2018).

The exceptional suitability of the Miura-Ori origami for engineering deployable or foldable structures arises from its remarkable degree of symmetry, showcased through its periodicity, and five fundamental geometric properties. The five fundamental features or the five fundamental geometric properties of the Miura-ori pattern are, rigid and flat foldability, one-degree-of-freedom, negative Poisson's ratio (this is the meaning of the pattern auxetic (symmetrical pattern), or when the pattern is expanded in one direction, this leads to a folded sheet that is stretched into an orthogonal, planar direction (Kamran, 2023)), self-locking (Xiang et al., 2021), and high energy absorption. These properties play a pivotal role in enabling the Miura-Ori origami to be seamlessly transformed from a planar, flat state to a configuration state by folding it (Kamran, 2023). Figure 10(C) depicts the folding mechanism of a Miura-ori pattern. Building the Miura-origami pattern can be done by the multiple unit's tessellation. Four identical parallelograms make up a unit that consists of it; see the cell of unit for the Miura-ori pattern in Figure 10(B). also, see Figure 10, where (A) presented the 2D unit cell containing the dashed lines, which presented the valleys, and solid lines, which presented the mountains; (B) is the Miura-ori cell of unit, and (C) is the motion (presented as expanding and contracting in all directions). The characteristics of Miura-ori can be illustrated by the following diagram, as shown in Figure 11.

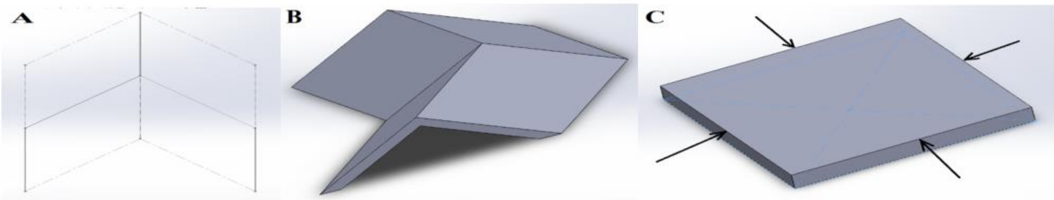

Figure 10. Cell of unit: (A) 2D cell of unit, (B) Miura-Ori cell of unit, and (C) Motion direction

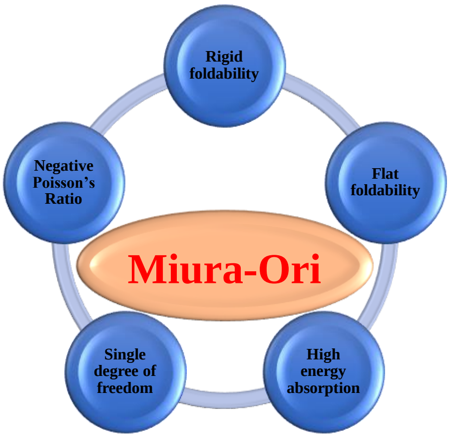

Figure 11. Characteristics of Miura-Ori

2.5.1 Structure Geometry of Miura- Ori

Miura-Ori is a repeated unit cell that is arranged with a rigid origami structure, and that's shown in Figure 8(E) (Xiang et al., 2021). The presence of folds and the geometric structure of the Miura-Ori structure have a significant job in achieving exceptional mechanical performance, such as adjustable stiffness (Nishiyama, 2012). The unit cell consists of four congruent parallelograms interconnected (Xiang et al., 2021). In other words, the use of zigzag patterns and parallelogram shapes by Miura-Ori made it fit for rigid bodies. Miura-ori was drawn by SOLIDWORKS software as a unit cell; after that, it was assembled for the formation of the Miura-ori sheet as displayed in Figure 12, where (A) is the one cell of the sheet pattern in 3D, (B) is the unit cell top view, (C) is the unit cell side view, (D) is the front view for the cell of unit and (E) is the pattern sheet of Miura-ori.

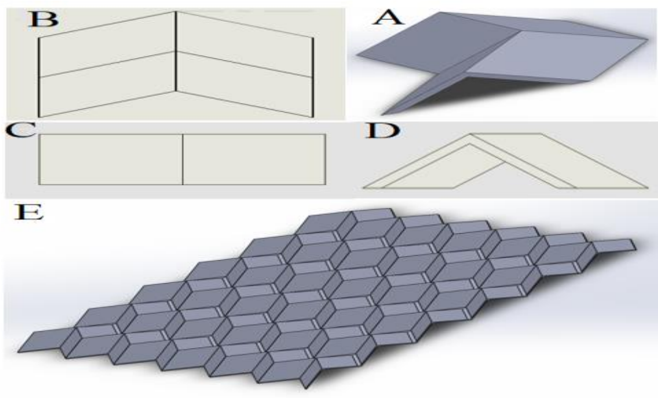

Figure 12. Unit cell and foldable sheet of Miura-Ori: (A) 3D unit cell, (B) Top view of the unit cell, (C) Side view for the cell of unit, (D) Front view of unit cell, and (E) Pattern sheet

2.5.2 Mathematical Model of Miura-Ori

Math is applied in origami in ways that have the most impact on origami's applications. When we about to fold a paper, the act itself mirrors the creation of a straight line. The magic lies in the fact that the various values of angle and numerical relationships, such as cosines and sines (Kamran, 2023) (Kunz, 2024; Schenk & Guest, 2013). The parameters of some types can be determined by a variety of methods. For miura-ori two methods were used: the lengths of the static folds (a) and (b) and the static interior angle (gamma). The dihedral angles of the tetrahedra and the XY plane are calculated simultaneously. The coordinates in the structural plane are X and Y; Z is coordinates outside the plane, and how the structure can be determined by the following scale parameters (Schenk & Guest, 2013); see Figure 13, where (a), (b), (H), (2s), (2L), and (V) present the dimensions while γ, φ, and θ present the angles. The equations (1), (2), (3), and (4) are used to find the dimensions.

$$H = a\, sin\theta\, sin\gamma \quad (1)$$

$$S = b\,\frac{\cos\theta\ \tan\gamma}{\sqrt{1+\cos 2\theta\,\tan 2\gamma}} \quad (2)$$

$$L = a\sqrt{1-\sin 2\theta\,\sin 2\gamma} \quad (3)$$

$$V = b\,\frac{1}{\sqrt{1+\cos 2\theta\,\tan 2\gamma}} \quad (4)$$

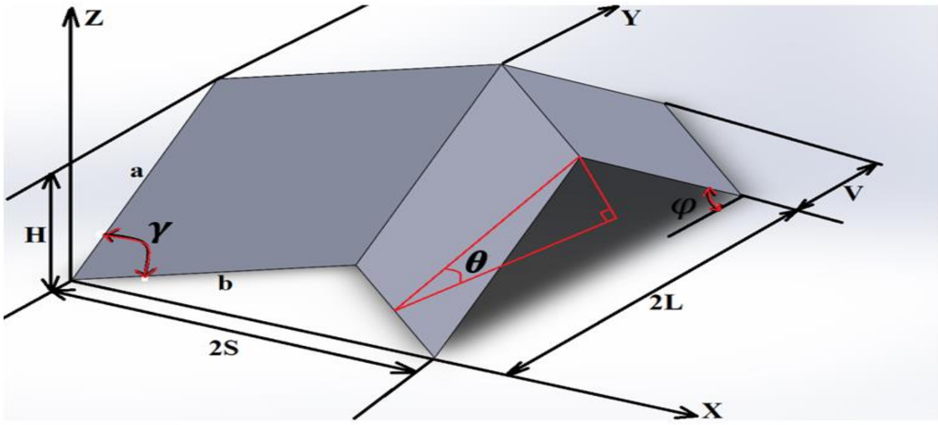

Figure 13. Mathematical model of Miura- Ori origami

The origami shapes can be elucidated in the following diagram as shown in Figure 14.

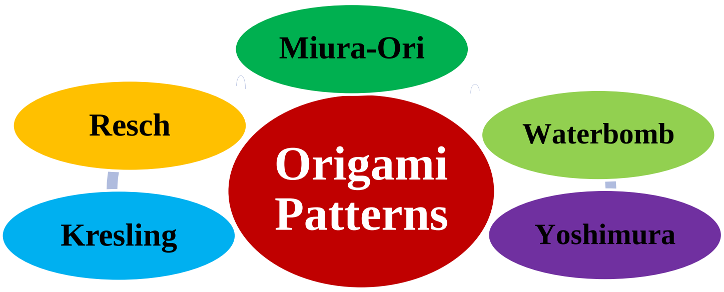

Figure 14. Origami shapes

3. Manufacturing of Origami

Manufacturing methods are materials dependent. Types of manufacturing have a direct effect on flexibility of corrugated sheet or origami. There are several methods to manufacture origami. Such that there is a novel manufacturing process proposed by Schenk and Guest, which folds sheets into Miura-ori by using cold gas-pressure (Liu et al., 2015; Zhu et al., 2022) (Chen Yao et al., 2022). One of the manufacturers used the stamping process to manufacture the corrugated sheet of composite materials for epoxy reinforced by fiberglass (Al-Jothery et al., 2020). The findings here present most commonly used processes for origami manufacturing in brief. The origami manufacturing methods are explained in the following diagram as shown in Figure 15.

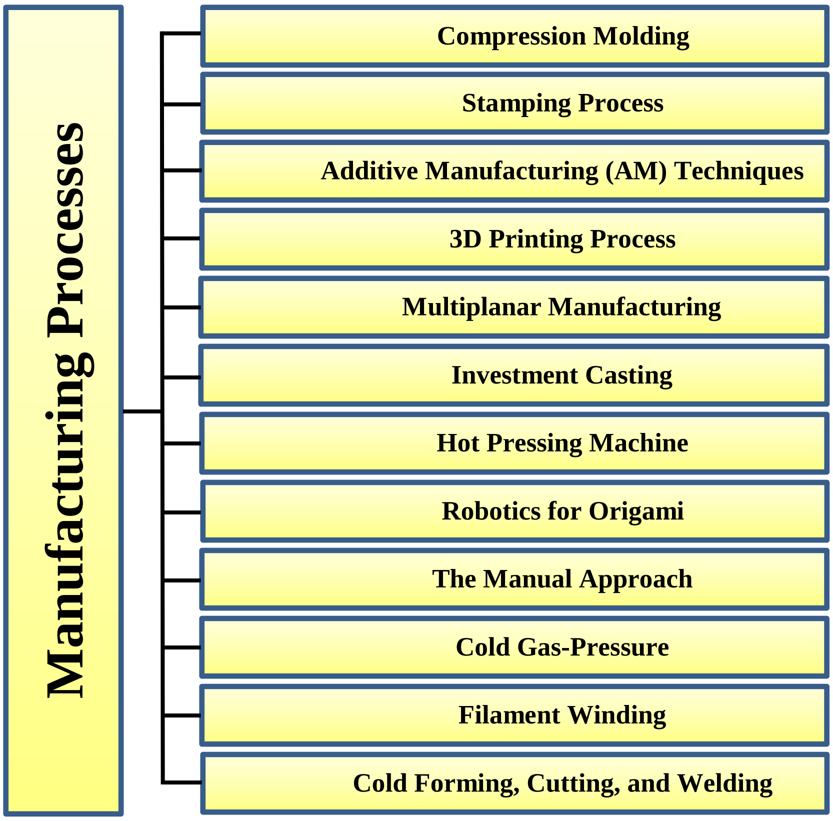

Figure 15. Origami manufacturing process

3.1 Compression Molding

This technique necessitates a compression molding apparatus and a corresponding mold.

3.2 Stamping Process

Due to the throng of parameters that required to be controlled, such as, the operation of forming with respect to the weight gage control, the material characteristic homogeneity, and the variety of types of material and grades, in addition to the different forming styles and the part shape. Therefore, press-based stamping is considered a complex process. 40 variables or more have a direct or indirect impact on the type of product as well as on the quality of the stamping process in general. In addition, this method can be expensive, especially for the equipment needed to design the mold and verify its accuracy (Qattawi, 2012). This method is used for thin sheet metal and for low-stiffness materials. In order to clarify this method, for example will be provided, manufacture the corrugated sheet (origami) of composite materials for epoxy reinforced by fiberglass (Al-Jothery et al., 2020).

3.3 Additive Manufacturing Techniques

Additive manufacturing (AM) is an ideal technology for manufacturing origami-inspired structures because it overcomes many of the challenges of manufacturing complex structures, especially those that face limitations in assembly and joining constraints. Metallic additive manufacturing has not yet been explored as a method for fabricating these structures in their configuration or their folded form (Harris & McShane, 2020).

3.4 3D Printing Process

Printing an origami pattern requires a 3D printer. Through using the Cure software program, the file is transformed from Autodesk Inventor part file (IPT) into Standard for the Exchange of Product data (STP). Origami pattern printing takes a long time. The printing process occurs in two phases to avoid the malfunction caused by power outages. The 3D printing process for origami patterns begins with a thermoplastic substance called Polylactic acid (PLA) filament. PLA filament is not affected by temperature changes during printing, as its temperature variation during printing, as its temperature ranges are 120 and

200 degrees Celsius. It can be melted via heating, while the base temperature of a 3-D printer is around 60 degrees Celsius. PLA is also considered easy to print (Kusyairi et al., 2019).

3.5 Multiplanar Manufacturing

This technique is another method to manufacture 3-D devices enthused by the art of origami. Typically, a monoplanar technique is used, which limits the origami to one plane through production, limiting its efficacy of design. In dissimilarity, when the hinges and panels are manufactured crossways at multiple levels, it provides higher flexibility of design as well as eliminates some assembly and adhesion processes. Multiplanar manufacturing have an effect on material usage, building footprints, and actuation requirements. In other words, it has great benefits of decreasing the usage of material till (62%), the steps of actuation till (93%), and the footprint of building till (91%). When comparing these benefits with a mono-planar shape in the geometries, these advantages enhance the efficacy and the assembly procedures that are opening up new avenues for origami-inspired device manufacturing (Stevens & Crane, 2025).

3.6 Investment Casting

Lost-wax casting, or precision casting, or Investment casting, has been a prevalent procedure for generations. It is renowned for its capacity to generate components with superior surface polish, precise dimensional precision, and intricate shapes, such as the types of origami patterns. The methodology of this process consists of a pattern usually made of wax by the desired shape, and in a metallic mold, the pattern is formed by injecting the molten wax. It is filled with molten metal and thermoset. The shell is broken, and the gates are cut off from the solidified casting to obtain the near net shape component, and this process is done after the molten metal is dried (Pattnaik et al., 2012). This method can create a complex product as well as not need many machined procedures, and it can be utilized in the production procedures of an origami pattern crash box since it is a complex product (Kusyairi et al., 2019).

3.7 Hot Pressing Machine

It is consider one type of compression molding for composites and polymers (Harris & McShane, 2020). Also, it is regarded as a complex process according to the amplitude of factors that are required to be controlled, like the shape of the part, various shaping styles, the forming process with respect to the tonnage control, temperature control, and the material characteristics homogeneity, as well as the different material types and degrees. Mostly, this method is used with the material that hardens with heating or for thermoset materials and thermoset composite materials. A number of researchers used this method for manufacturing origami but with different parameters, such as the corrugated sheet for epoxy reinforced by fiberglass. In other side (Liu et al., 2015) took one parameter only while neglecting the other parameters. Figure 16 shows the hot-pressing machine.

3.8 Robotics for Origami

For products Origami-based manufacturing requires robots capable of folding and bending many materials. Therefore, the robots that bend the normal paper origami were for discovering and exploring the problems connected with modeling, manipulation, and foldable structures' design. Consequently, this robotics can execute the complex functions (Abtan, 2019; Turner et al., 2016).

3.9 The Manual Approach

The manual method compresses cutting the faces (geometrical form) from a solid substance as well as sticking them upon a flexible sheet for manually forming the crease pattern. And the fluctuation hinge is the flexible substance between the face edges; this material acts as a fluctuation hinge. This method was considered the commonly used and the conventional method (Abtan, 2019).

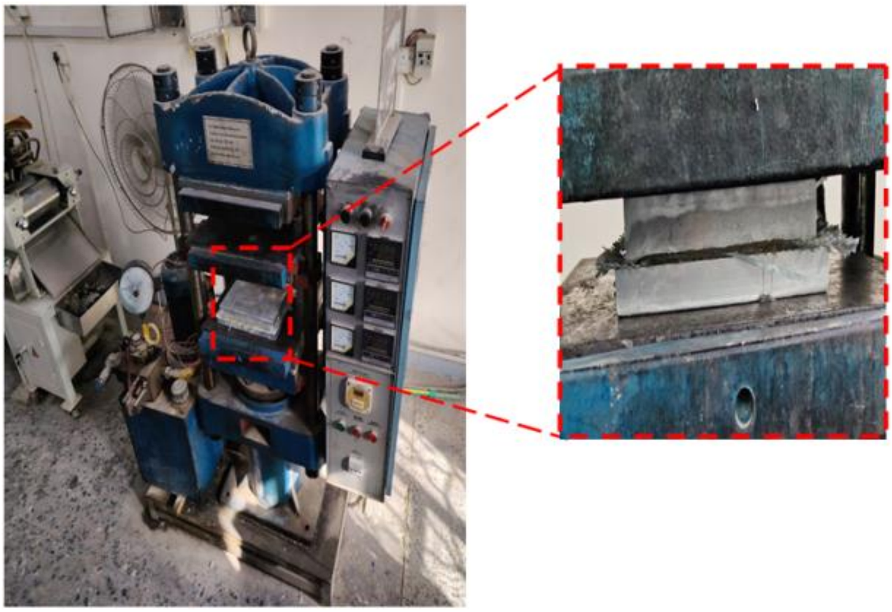

Figure 16. Hot-pressing machine

3.10 Cold Gas-Pressure

As a brief explanation of the process firstly, the folding pattern is imprinted onto the metal sheet, and then along the lines of the fold, the material is weakened. A set of techniques achieves this, for example melting, embossing, etching processes, etc. In the present work initial application, a created simple perforation pattern is along the lines of the fold. After that, in a structure of sandwich, the two such sheets are packed, and the two such sheets are separated by a series of simple spacers that are put into slots along the 'mountain ranges of the economical fabrication of composite cylindrical tubes. This approach merges the advantages of origami with those of carbon fiber reinforced epoxy resin materials, offering weight-saving benefits compared to metals due to their superior strength and stiffness-to-weight ratio (O'Neil, 2024). Filament winding is used to effectively produce pre-folded carbon fiber reinforced plastic (CFRP) tubes. Most of the Kresling origami tubes are built with filament winding method. And a Kresling origami formed mandrel for carbon fiber were permitted to rotate the motion around its axis with pull at the same time (O'Neil et al., 2023).

sheet. Into an airtight bag, the combination is packed, which is evacuated to near vacuum, combined with a growing external pressure. This pressure difference forces the sheets to bend simultaneously along all lines of fold. finally, the relatively thick sheet materials can be formed using this process by topping up the external pressure (Schenk et al., 2011).

3.11 Filament Winding

It is a process of manufacturing widely employed in industry for the

These were the most prominent manufacturing processes that were highlighted, and they are in fact the most famous processes in origami production. It is worth noting that there is no method that is preferred over others, but rather each method is used according to its circumstances, required parameters, and the basic material from which origami is to be made, as mentioned previously.

4. Origami Applications

The origami method has been used in numerous manufacturing uses and confirmed to be useful in areas like packaging design and architecture (Fei & Sujan, 2013). Researchers observed that the old folding and geometry utilized in the paper art models could be easily developed as well as modified to create new devices (Xiang et al., 2020). So many applications of origami are involved in several fields of engineering specializations. Applications of origami span from ancient Japanese traditions to astronautical engineering (Nishiyama, 2012). For example, in mechanical engineering, they include absorption energy, solar panels, crash boxes etc. In medical engineering, they comprise surgical devices, stents, and furniture of flat-foldable (Sciences, 2016). In buildings and structures origami such as Miura-ori shapes can be implemented in the building field for designing expandable and foldable construction components. For instance, soundproof walls, expandable sunshades, and roofs that can be automatically expanded or folded as required for controlling insulation and lighting, insulation of sound, or even for saving energy (Liu, 2023). This review focused on the applications of automotive, Aeroplan, Aerospace, Buildings and structures, medical equipment, Map and floor plan and Architecture for origami structures. In brief, the origami applications are explained in the following diagram as elucidated in Figure 20.

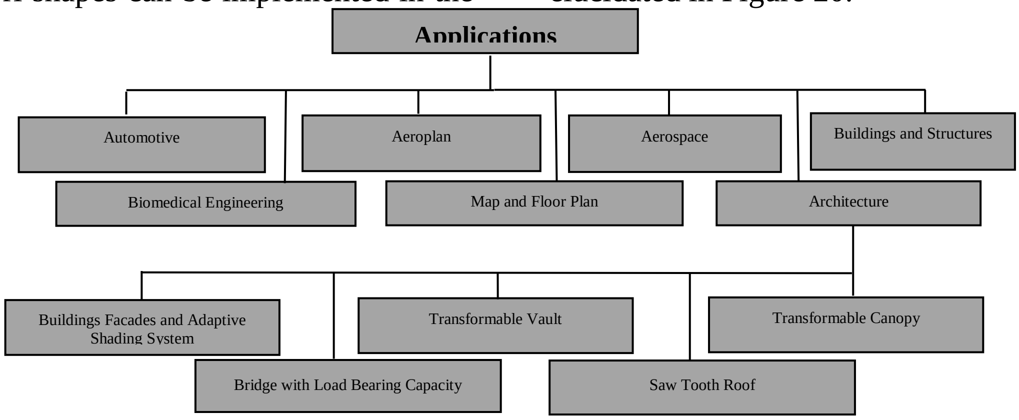

Figure 20. Origami applications

4.1Automotive

Car airbags were designed to be folded compactly; this technique made them quick to deploy. Each airbag had the ability to deploy within milliseconds. This effectiveness stemmed from the three-dimensional shape of the airbag. It utilized the concepts of rigid origami and its ability to fold flat to create the folds that flatten the airbag (Turner et al., 2016). However, automobiles equipped with origami crash box are effective in absorbing the energy and thus protecting lives (Liu, 2019). Design for crashworthiness in origami crash boxes was studied, and proved that the origami structures have a higher energy absorption than the conventional structures (Al-Jothery et al., 2020; Zhou et al., 2017).

4.2 Aeroplan

Since origami is one of the forms of corrugation. Therefore, origami can be used as the core of sandwich structures (Liu et al., 2015). Sandwich structures are widely used in aircraft industries due to their high stiffness-to-weight ratio and configurable energy absorption performance (Boreanaz et al., 2020; Hüseynli, 2016; Liu et al., 2015). In conclusion, lightweight sandwich panel of Origami was the suitable cores for aircraft fuselages (Admin, 2016).

4.3 Aerospace

In space, they have proven to be useful for foldable sunshields and solar sails (Wagner et al., 2020). The method of folding is called Miura-Ori which had been introduced in shapes section in this paper (Fei & Sujan, 2013). Solar panels used Miura folding to unfold in space in order to gather the solar energy, because it takes less space if folded (see Figure 22). Furthermore, the folded and unfolded panel causes the panel angle to be able to become automatically modified in accordance with the lighting and position circumstances of the sun and that improves the energy efficiency. Among the space applications are the telescope of Space and Eye glasses: Robert Lang designed a foldable telescopic lens that can be simply packed into a space shuttle and then deployed in space via employing origami methods (Fei & Sujan, 2013). Back to where one started, one can say that the inflatable origami structures have been proposed for aerospace applications due to their high deployment ratio, low system complexity, and simple deployment mechanism (Santos Lula Barros et al.). Other applications in aerospace are called multi-stable Miura-Ori and Kresling bellows; their application is deployable space habitats (Yang et al., 2023). Before expanding once in orbit, such habitats would be compactly stowed during launch (Yang et al., 2023).

4.4 Buildings and Structures

Many engineers have focused on the structural integrity of dynamic designs, using geometric transformation to achieve multiple objectives within a single context (Meloni et al., 2021). A good example of origami applications in buildings and structures is Miura folding, which can be implemented in the building field in order for designing expandable and foldable structure components. And, for instance, soundproof walls, roofs, or expandable sunshades, can be automatically expanded or folded as required for adjusting the lighting, saving the energy, and even providing the sound insulation. In addition to that, the Miura-folding structure is utilized for building steady bridges and buildings for improving their earthquake and wind strength. Also, It can be utilized as a share of sandwich structure that plays the part of the insulation of sound and the dampening (Liu, 2023).

4.5 Biomedical Engineering

Biomedical industry is considered the highly important progressive fields in the origami-based advice use through research or application. The vital role of medical equipment in human life, therefore, it takes interest in the biomedical engineering field. Medical equipment is biomedical engineering-based. Origami is associated with this equipment; therefore, biomedical engineering is mentioned here (Meloni et al., 2021). The best example of the application in the field of medical equipment is medical robots. Medical robots are constructed by using origami structure. Sargent and colleagues proposed an origami-based system (Ori-Guide) to improve external support of the body by inserting flexible instruments into the RAS by using the Kressling pattern with a cylindrical structure. And they designed an anti-flexion system, which supports an endoscope used for bronchoscopy surgeries. In the previous example it was about the Kresling pattern but for Miura pattern can be used to design foldable medical equipment, such as surgical screens, patient isolation screens, portable medical instruments, and so on. To provide necessary functions, the devices features are folded when not in use, allowing easy carrying and storage, as well as, rapid expansion if required (Liu, 2023).

4.6 Map and Floor Plan

Miura-ori is considered the best example for a map as well as a floor plan. And the map can be blended into a smaller dimension, which being easy to carry and store, and then separated for viewing the details if required. Such a process is too important for travel, outdoor exploration, and emergencies, (Liu, 2023).

4.7 Architecture

In recent years, the developments in contemporary architecture have led to a produced building skin element complexity, therefore unveiling of fresh flexible, expand, and adjustable solutions (Tsiamis et al., 2018). For example, the geometric characteristics of folded origami tessellations are flexibility, combined with the structural efficiency of folded plate structures, and a light and stiff structure that moves in space with the consistency of simple planar and creases (Tsiamis et al., 2018).also, the origami-based designs could be capable of reducing the energy demand, offering improved structural achievement, and evolving the adaptive as well as the climate responsive designs, despite often being adopted for purely aesthetical purposes. Also, self-actuation that is the origami-based designs ability for actuating their deployment with no additional exterior actuators. For Miura-ori in particular, it has been applied to the folding of deployable structures for various architectural applications, such as shelters and folding roofs (Sareh & Guest, 2014). In conclusion, in the engineering of facade technologies, the origami-based designs obtained remarkable uses because of thanks to the ability to be applied in the curved and flat surfaces, be re-configurable and hierarchical kinetic structure designs, and allow tessellations (Meloni et al., 2021). Some architectural applications are reviewed and described here

4.7.1 Buildings Facades and Adaptive Shading System

The first line of defense against the conditions of the environment is facades. To encase that inhibits or permits the sunlight to penetrate the building, some of the buildings use a dynamic shell (consisting of many elements). Their use would increase interior visual comfort (i.e., interior lighting levels), as well as provide significant savings in energy consumption and reductions in carbon emissions, which are the big benefits. Therefore, it is very important that such elements (elements of dynamic shell) adhere to the principles of origami to alter their properties instantaneously. In other words, according to the momentary interest, it is adjusting their position and size. This led to allowing or blocking the light flow (Pavón et al., 2022).

4.7.2 Transformable Vault

The application displays tubular morphology. A domed structured with adjustable length and cross-section is a typical one of origami pattern. To illustrate this tubular pattern and its structure by nature, it's like worms that are capable of contracting their long muscles to shorten and thicken them or contracting their surrounding muscles to lengthen as well as thin them. Alike ideas of geometrical expansion can be made using origami folding, and the domed structure is one such concept (Liapi, 2002). In architectural engineering, the vaulted structure that can regulate the cross section and length for fitting to a hole is a likely use in such a field.

4.7.3 Transformable Canopy

A multitude of plants, along with abundant flower buds, form a delicate, continuous membrane and exhibit two distinct morphologies over their life cycle: Initially, at a specific phase in their life or the early part of a daily cycle, the folded membrane develops into a cylindrical hub. In a more advanced phase of their life, or during another segment of the diurnal cycle, the membrane expands to create an almost flat surface perpendicular to the initial orientation of the folded membrane. This notion served as a prototype for an initial investigation of a spatial covering system. The objective was to construct a modular framework consisting of bud-like elements and strive to develop it. Units form a continuous overhead surface in the unfolded configuration to furnish a canopy for shade or rain protection. In the early 1960s, the mathematical properties of a membrane packaging diagram with characteristics analogous to the blossoming of flower buds, inventions were conceived (Liapi, 2002). The proposed approach has an additional benefit in that via incorporating in the digital kinematic model of the origami kind structure with architectural factors like texture, light, shadows, color, and translucency of surface etc. (Liapi, 2002, p. 7).

4.7.4 Bridge with Load Bearing Capacity

Load bearing structures like bridges can be made with origami modules. Group of researchers are based on a novel approach with a new study to designing super-rigid deployable constructions. These researchers used a new methodology to design bridge structure. And their delineation relies upon tubular constructions blocks constructed with a uniform folding pattern called Miura-ori transforming a flat sheet into a deployable structure possessing a singular degree of freedom. Two Miura tubes can be placed side by side in a zigzag pattern. These two tubes together (pair) possess remarkable stiffness, possessing a single degree of freedom due to their resistance to else bending as well as twisting styles. Also, these zipper tubes can be joined to create else constructions, comprising cellular assemblies and tubular regimes that have a high complexity. Figure 21 shows a model bridge that's designed via number of researchers. Including a sequence of zipper-combined tubes; it was considered Origami-inspired engineering (Reisa et al., 2015).

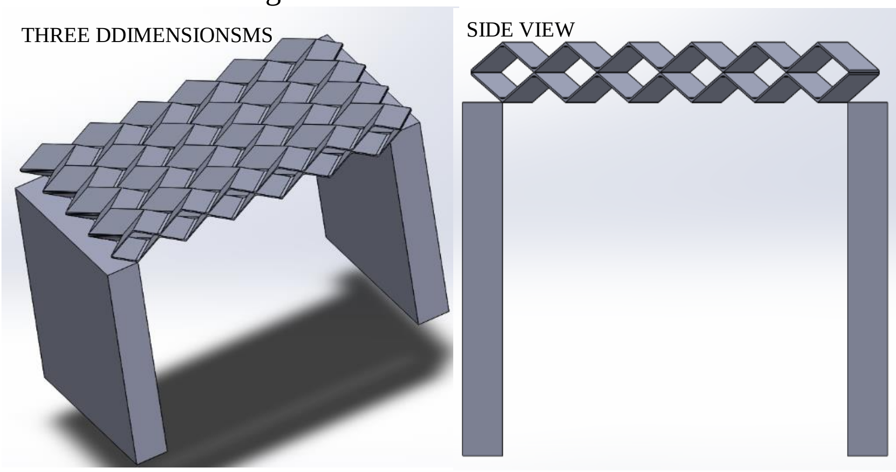

Figure 21. Model bridge designed using origami structure

4.7.5 Saw Tooth Roof

The saw tooth roof of numerous manufacturing works is a simple example in architecture engineering that simultaneously gives improved out-of-plane stiffness of the roof diaphragm and the best natural ventilation and light circumstances in their inner (Reisa et al., 2015, p. 2). The saw tooth roof was derived from the idea of origami. The windward roof geometry of a sawtooth building influences cross ventilation flow (Peren et al., 2015). According to Peren et al. (2015) study, the two different roof geometries studied (inspired by origami) include the first one that's concave and second one that's convex roof geometries. The geometry of the convex roof increases the pressure under the building's surface where the outlet is located, which enhances cross-ventilation flow due to the wind. By comparing the convex and concave roof geometry, it was observed that the sawtooth convex roof geometry facing the wind resulted in an increased volumetric airflow rate. Therefore, the increase in indoor air velocity can reach up to 90% in the upper, habitable area of convex roofs compared to concave roofs (Peren et al., 2015).

5. Conclusion

This paper presented the fundamental concept of ORIGAMI engineering for the shapes of origami with their application and manufacturing methods. However a comprehensive examination or overview of origami-inspired structures is discussed in this article. In part one of this paper, according to the shape of origami, the five main known ones were discussed, and then it focused on the geometry of Miura-Ori. The second part was about manufacturing processes, where twelve methods were presented for this purpose. There is no method that is preferred over others, but rather each method is used depending on the basic material from which origami is to be made. Finally, for origami application, highlight seven fields only due to the lack of space to mention more than that, knowing that its applications are countless. By reading this review paper on origami-inspired structures, one hopes that the knowledge about this engineering art, with its other forms and its other manufacturing methods, will increase more and more. Add to that research into its application to every engineering field used in life in order to improve the sustainable use of space and weight. This topic is not without future studies on it.

6. Recommendations

1. Pattern Innovation: Explore novel origami patterns beyond the five established types, leveraging computational tools (e.g., SOLIDWORKS, generative algorithms) to design shapes with enhanced mechanical properties or multi-stability.
2. Advanced Manufacturing: Investigate hybrid manufacturing approaches (e.g., combining 3D printing with smart materials) to address limitations like joint fatigue in additive-manufactured origami. Expand material research for 3D printing to include biodegradable polymers or shape-memory alloys.
3. Application Diversification: Document origami applications in emerging fields (e.g., renewable energy systems, soft robotics, wearable technology) and daily-use products (e.g., foldable furniture, emergency shelters).
4. Sustainability Integration: Optimize origami designs for circular economy principles, focusing on recyclable materials and energy-efficient production.
5. Interdisciplinary Collaboration: Foster partnerships between mathematicians, engineers, and architects to develop standardized testing protocols for origami-based structures and accelerate real-world adoption.

These steps will bridge existing knowledge gaps and unlock origami's full potential in next-generation engineering solutions.

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