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Origami engineering: Creating dynamic functional materials through folded structures

Mohit Kshirsagar [a], Siddhi D. Ambike [b], Niranjana Jaya Prakash [c], Balasubramanian Kandasubramanian [c,*], Pradnya Deshpande [b]

[a] Department of Fibres and Textile Processing Technology, Institute of Chemical Technology, Mumbai, 400019, India
[b] School of Chemistry, Dr. Vishwanath Karad MIT World Peace University, Pune, 411038, Maharashtra, India
[c] Additive Manufacturing Laboratory, Department of Metallurgical and Material Engineering, Defence Institute of Advanced Technology(DU), Girignar, Pune, 411025, Maharashtra, India

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ABSTRACT

The scientific community has displayed an increasing interest in the materials and strategies for the development of origami structures capable of undergoing 2D to 3D transitions owing to their potential to create materials possessing fundamentally new functionalities and characteristics. Thin film residual stresses, mechanically active materials, or forces that arise from capillarity have been used as a mechanism to undergo folding deformations in engineered structures inspired by origami and have found potential in multiple arenas. The self-assembling, shape memory, and reversible properties of these smart materials have aided in maintaining the desired structure, and the ability of the material to withstand change after exposure and regain its original shape, which, encouraged this emerging innovative approach to meet current needs. In this article, a primary attempt has been carried out to consolidate the origami revolution over the last decade in various emerging fields, as well as its future applications and challenges. The emphasis has been provided on the designing of origami structures that permit the operationalization of advanced macro to nano-scale materials in 3D functional structures that have expanded their reach to multiple fields such as spacecraft, robotics, lithium-ion batteries, and biomedical applications.

1. Introduction

Materials that range from macro to nano-dimensions are subjectable to dynamic mutual interactions and translational dynamism, and the potential to control these interactions holds the key to the development of functional architectures. Engineering self-organization, molecular level manipulation, chemical nanofabrication, and field-controlled organization is the most formidable task in the development of complex 3D structures with novel functional and structural properties [1]. Various techniques including interference lithography, fused deposition modeling [2], photolithography, and injection molding have been developed to date for the fabrication of such structures, the technique used will depend on several criteria including the material properties, scale, intricacy of design, and use of the origami structure. Recently, the origami approach utilizing the controlled bending or folding of thin films has been garnering a lot of attention owing to their reproducible, quick, and reversible nature in the fabrication of hollow 3D structures with controlled interior and exterior morphology and chemical properties [3]. Origami refers to the traditional Japanese art of folding uncut sheets of paper sheets into various 3D objects where basic origami was practiced with paper and is generally considered as a foundational step in practicing model designing. However, currently, the term origami is utilized by the scientific community referring to the art of developing smart 3D complex materials from 2D structures by employing various mechanisms such as folding, unfolding, and twisting, to improve the structural as well as the mechanical properties [4]. The stimuli-responsive behavior of these materials activates the origami structures when they are disbanded from isotropic to anisotropic in nature transforming from 2D sheets to 3D structures as shown in Fig. 1. The physiochemical property of materials responds to external factors such as temperature/heat, electric fluxes, environmental factors, pH change, and magnetic fields [5]. Throughout its extensive historical lineage, it has been designated under a myriad of nomenclatures, notably “orisue “and “orikata” [6]. Despite its traditional origins, it is

* Corresponding author.
E-mail address: meetkbs@gmail.com (B. Kandasubramanian).

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essential to underscore that substantial practical applications have primarily emerged within the preceding 5 decades. Notable examples include the utilization of origami-based bellow used in mechanical systems, foldable proteins to attain optimal functionality, biomechanical systems, metamaterials, robotic systems, deployable architectural infrastructures, engineering devices, and reconfigurable aerospace applications. Between the 1970s and the early 2000s, a series of theories were proposed to elucidate the historical development of origami simulation techniques. Huffman [7] and Resch [8] exemplify the incipient initiating in origami simulation folding techniques in the virtual domain. Resch and Christiansen strategically utilized linear elastic rotational hinges to facilitate the folding of creases, demonstrating a methodical approach to origami-based engineering [9]. Subsequently, in the year 2010 and beyond, researchers embarked on a systematic exploration of origami as a foundation for designing various metamaterials, impact-absorbing structures, and engineering systems [10] [–] [12]. Advanced origami simulation techniques have been developed to scrutinize the intricate kinematic, mechanical, and multiple physical characteristics exhibited by these delicate sheet-based structures. Origami structures have an advanced degree of freedom that came from bending, stretching, and shearing of panels. Simulations based on rigid origami models fall short in accurately representing the authentic physical behavior inherent in origami structures. This simulation technique also helps to analyze kirigami systems. The introduction of computational tools and designing software, marked a significant advancement, enabling researchers to model and simulate the complex behaviors of origami structures under various conditions. These simulations provided invaluable insights into the mechanical properties and potential applications of origami. As digital origami software and design tools emerged, designers gained the ability to create and test virtual origami structures swiftly, allowing for rapid prototyping and visualization of intricate folding patterns. Researchers harnessed origami simulations to optimize robot configurations and folding patterns, design deployable structures for space exploration, and create innovative medical devices. Simultaneously, advances in material science introduced smart materials, such as shape memory polymers, which responded to external stimuli, further enhancing the versatility of origami-inspired solutions.

Kshad et al. experimented with origami by using the sandwich pattern with polymeric materials such as thermoplastic polyurethane (TPU) and Polylactic acid (PLA) with varying compositions of TPU from 0 to 100%. It was observed that the outer PLA component provided improved stiffness to the composite, whereas the TPU core provided superior energy adsorption efficiency acting as the hard and soft phases providing permanent and temporary net points respectively [13]. In addition, Feng et al. experimented with fibers and arrangements in CFRP composites, and Miura-geometric ori's parameters were utilized to regulate the stiffness and NPR of such structures in shock absorbers and space applications and rapid deployment structures [14] (Supporting S4). A finite element analysis study showed that the Miura-ori structures made of CFRP composites can achieve higher stiffness and Poisson's ratio values than isotropic materials like aluminum [15]. However, most of the origami structures developed utilizes synthetic non-biodegradable materials which can cause adverse biological and environmental implications, which has led to the development of origami structures using natural and biocompatible materials. Chen et al. experimented with silk fibroin (SF) film which was a promising biodegradable natural solution for replacing synthetic polymers having the same mechanical properties, where origami foldable SF films stand as structural regulators of SF molecules using water and formic acid. SF film has exceptional breaking strength, and modulus, and can endure 1000 times its weight while being folded into complicated three-dimensional shapes without destruction.

In this comprehensive paper, we have undertaken a thorough exploration of origami, delving into its diverse properties, multifaceted involvement in various fields, and wide range of applications. The art of origami offers a distinctive set of structural mechanisms that greatly enhance mechanical and physical properties across various contexts. Our study focuses on the advanced applications of origami, particularly in conjunction with smart materials such as shape memory polymers (SMPs), self-assembling polymers, hydrogels, elastomers, etc. Notably, we have dedicated meticulous attention to the design and implementation of these smart materials, utilizing the miura-ori structure, honeycomb origami, and other intricate tessellations. Furthermore, we have introduced kirigami as a means to introduce advanced modifications to origami structures, adding an additional layer of sophistication to our research. Designing complex structures using software involves precise digital design, structural analysis, and simulation. Direct and indirect design software is vital for precision, efficiency, and customization across industries. Advanced manufacturing methods like 3D printing or CNC machining translate digital designs into physical structures with unparalleled accuracy. Origami-inspired techniques hold substantial potential across diverse domains. They open doors in 3D printing, enabling the creation of intricate, customizable structures for packaging, artistic expression, and practical applications. In the arena of spacecraft design, origami's compact and deployable attributes stand to revolutionize launch logistics, reducing both size and cost. Biomedical applications, too, are poised for transformation as origami brings forth compact, expandable medical implants, paving the way for minimally invasive surgery and innovative drug delivery systems. Furthermore, origami principles promise to optimize lithium-ion batteries, granting them flexibility and compactness, ideal for portable electronics. Within the realm of robotics, origami-inspired designs bestow adaptability and shape-shifting capabilities, positioning them for diverse applications ranging from search and rescue missions to the rigors of space exploration. Beyond these, origami's influence extends to the development of metamaterials, where its unique properties impact

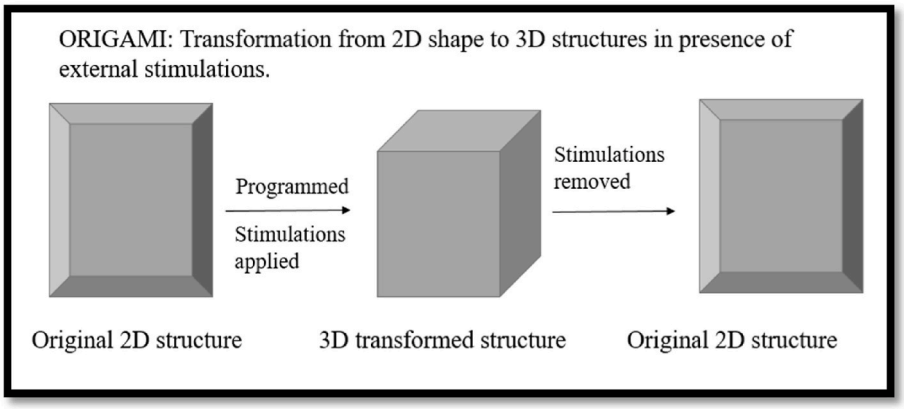


Fig. 1. Origami transformation from 2D to 3D sheets when exposed to external stimulations.

technologies like cloaking and signal manipulation. As researchers delve deeper into origami-inspired applications, we anticipate transformative breakthroughs that will redefine industries and propel the frontiers of science and technology. Our aim is to inspire researchers and innovators to explore and harness origami's transformative capabilities across diverse domains.

2. Shape memory polymer (SMP)

Shape memory polymers (SMPs) are a class of intelligent very smart materials known for their remarkable properties, enabling them to be utilized in structures inspired by origami. These materials possess the unique capability to return to their original shape from the deformed shape in response to external stimuli like pH, temperature, and chemicals, the polymer does not undergo degradation after continuously repeated cycles. Reversible change of shape memory polymer is the function of the "Entropy elastic phase" [16] and "switch phase" [16], The term "Entropy elastic phase" refers to the high-temperature phase in which polymer chains within SMPs are randomly coiled. This phase exhibits a soft and flexible behavior allowing SMPs to easily deform when heated above transitional temperature, while the "Switch phase" refers to the low-temperature phase of SMPs. In this phase, the polymer chains become more ordered and exhibit a rigid behavior. The molecular when cooled below the transitional temperature. The glass transition temperature (Tg) is linked to changes in the entropy (S) of the system, particularly the entropy associated with the structural deformation of the atomic or molecular arrangement as the material undergoes the transition from a liquid to a glassy or amorphous state. This relationship between Tg and entropy is a key aspect of understanding the glass transition phenomenon in supercooled liquids. This idea is based on the Adam-Gibbs Model, which describes how extremely cold liquids and glasses behave, [17,18]. Reduced entropy, which indicates lower atomic mobility and enhanced order, is a common feature of Tg. Rapid Tg transitions with noticeable entropy and viscosity shifts are characterized by fragility. The importance of entropy in structural transition is that it decreases with increasing order, which is connected with higher viscosity and less atomic mobility. In some models, entropy is used as a parameter to characterize the transition, highlighting the entropy drop that causes the change from liquid to glass. Entropy variations have a significant impact on the complicated glass transition, where a decrease in entropy denotes a fundamental change in amorphous materials. A thermomechanical testing [19] represents the established methodology for assessing the mechanical and shape memory characteristics of shape memory polymers (SMPs), The 3D Stress-strain-temperature relationship illustrated in Fig. 2 provides a comprehensive understanding of the behavior of a material under different conditions (Fig. 2). In Section A, (elevated temperature T_h) $T_h > T_{trans}$ at this temperature SMPs exhibit temporary shape when subjected to an external load, thus the material can be deformed and retain a deformed shape as long as an external force is applied. In Section B, (new Temperature T_1) $T_1 < T_{trans}$ in the presence of external force, (SMP) remains in temporary shape even T_1 is reduced than transitional temperature. In Section C, at T_1 external force is removed therefore stress decreases and the material starts to recover in its original shape but not fully recovered due to some stress is present. In Section D, shape memory polymers (SMPs) are heated above (T_{trans}) the temperature increases, therefore it returns to its original shape from a temporary shape (T g), the elastic modulus refers to rigidity, with necessary structural support being provided for folded and creased, higher hardness helps to maintain the integrity of the folded structure, flexibility allows (SMPs) to fold and unfold repeated cycles, (SMPs) have damping properties can absorb or dampen vibration, vibrational oscillation, providing stability in origami structures. Additionally, specific dielectric properties of (SMPs) can be used for origami-inspired electronic devices and sensors [20]. Shape memory capacity have the ability to store or recover strain energy, they are characterized by shape fixed ratio (Rf) and shape recovery ratio (Rr) respectively [21,22], calculated by the formula:

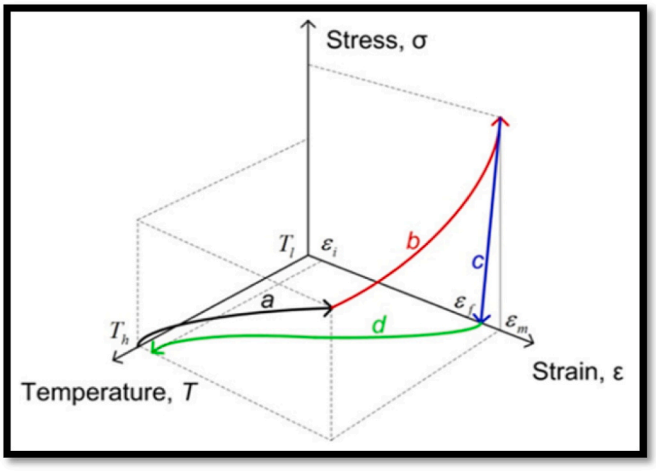


Fig. 2. Stress-Strain -Temperature Relationship (thermomechanical test). Reproduced from Ref. [19] with permission from Elsevier 2011.

$$R_F(X \to Y) = \frac{(\varepsilon_Y - \varepsilon_X)}{(\varepsilon_{Y1loading} - \varepsilon_X)} \times 100\% \quad (1)$$

$$R_r(X \to Y) = \frac{(\varepsilon_X - \varepsilon_{Yrecovery})}{(\varepsilon_X - \varepsilon_Y)} \times 100\% \quad (2)$$

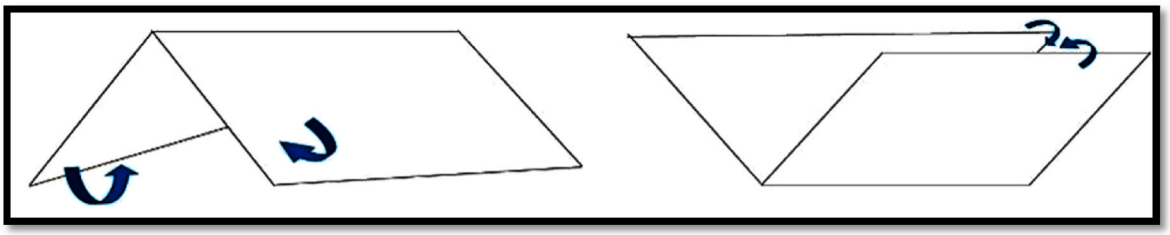
ε = *strain*

T_h is elevated temperature
T g is glass transition temperature
X and Y are different shapes
Loading – strain before unloading
Recovery – strain after recovery
(Elevated temperature T_h)

3. Designing

The deliberate arrangement of the geometrical patterns or folding lines within a specified region of the 2D sheet, generally known as a crease pattern, defines the origami. The crease pattern of an origami comprises vertices, facets, and creases, where a crease indicates the line along which the material folds and the vertex is the intersection of two or more folds, the crease is a concave (valley) or convex fold (mountain). When all of the creases are put together, the crease pattern is created. The amount of creases originating from a vertex determines its degree where the folded state is the consequence of an observable folding action (as shown in Fig. 3) [29]. The characteristics of these origami structures are highly dependent on the crease patterns that differ with the kinematic relationships and geometrical features, by embracing innovative design techniques and exploring novel approaches, a diverse range of origami structures with multistable states have been successfully fabricated. The most popular crease patterns are the Miura pattern, Waterbomb pattern Yoshimura pattern, which are types of tessellation origami. Tessellation origami represents harmonious blends of artistry, mathematics, and ingenuity to create beautiful designs.

The origin of origami started as a traditional artistic expression and hence is too arbitrary to be applied in scientific research. However, there exists certain assumptions on the fundamental theories of origami engineering, specifically for design which unites origami and kirigami research efforts within a broader engineering perspective. Santangelo et al. listed out some assumptions to guide one's understanding of origami structures [30].



a) Mountain fold b) Valley fold

Fig. 3. The folded pattern of material for the mountain fold and the valley fold.

- Single sheet Folding: Ideal origami uses a single sheet of material without the need for it to be cut.
- Continuous Deformation: The origami is supposed to deform from a flat, unfolded state into a folded configuration, ensuring smooth and gradual transformation of shape, allowing for mathematical analysis.
- Planar Embedding: Origami structures can be embedded in a plane (2D surface) without self-intersections or overlaps. This feature simplifies the mathematical representation and analysis of folded patterns.
- Rigidity Preservation: Origami structures maintain rigidity in certain regions, even while undergoing complex folding. This assumption highlights the stability and structural integrity of origami designs.
- Structures are composed of elements - vertices, edges, and faces - that are theoretically zero-dimensional points, one-dimensional lines, or two-dimensional planes. In practice, these elements have thickness and dimensionality, leading to the study of "thick" origami structures in theoretical work [31–33].
- Origami edges are typically assumed to be perfectly straight, and faces are not expected to bend. In reality, curved folds and face bending are observed in practical origami [34,35].However, the assumption of straight folds is often maintained, and when faces do bend, it can be approximately modeled by introducing auxiliary folds along diagonals.
- The assumption that origami edges do not stretch is made for simplicity, although it doesn't hold in real-world scenarios. In cases where the bending-to-stretching stiffness ratio tends to zero, this assumption becomes more valid, especially when the material is thin and external forces are minimal.
- Origami, in its purest form, does not involve gluing, cutting, or rearranging folds and vertices. While origami allows for the possibility of holes and cutting, the concept of "gluing" deviates from traditional origami principles. "Kirigami," which often involves cutting and rearranging, can be seen as an extension but does not always align with artistic or scientific definitions. In practice, maintaining the no-gluing assumption is experimentally feasible [36].

There exist some proven theories on the design methods of origami.

3.1. Tree method

The tree method is the main practical technique for creating desired origami shapes. It suggests that tree-shaped origami can be crafted by arranging circles and rivers within a square. Lang et al. expanded on this theory, providing explanations, mathematical proofs, and a computational algorithm [37]. This algorithm, within specialized origami design software, called "TreeMaker," generates a crease pattern that, when folded, mirrors the intended tree shape, accommodating edge length variations. However, it mainly influences one-dimensional characteristics, such as flap lengths. Achieving the desired three-dimensional configuration often requires an experienced origami artist's intervention to shape the base manually. Even among skilled practitioners, creating a desired three-dimensional shape through the tree method remains a challenge.

3.1.1. Polyhedral folding

Polyhedra are created by folding a square sheet of paper [38]. The core concept is to fold the square sheet into a thin strip and wrap it around the desired polyhedron. However, this method is impractical due to its use of an overly narrow strip, which results in inefficiency and an inability to consistently maintain the correct three-dimensional shape. An alternative method involves paper folding to achieve the desired polyhedron, but it faces similar practical issues. The folded form is unstable, and the crease pattern generated is inefficient, primarily stemming from the algorithm's initial phase, which creates a complex tree-shaped polygon.

3.1.2. Tucking

By tuck folding, a flat piece of paper may be bent. Tuck folding is a technique used by certain origami artists to create three-dimensional surfaces. Based on this idea, a method for constructing three-dimensional origami surfaces by tucking and hiding undesirable paper portions has previously been proposed. With this technique, the concept of "tucking molecules," or pieces of a crease pattern created just for tucking, is introduced. The design process, however, relies on trial and error using standard paper craft software and vector drawing software because no method or system has been created. It can often take many weeks to develop a crease pattern for a three-dimensional origami model using this method [37].

Robert Lang proposed 4 laws of Origami.

1) The First law: Law of 2 Colourability - With just two colors, you can color any crease design without ever having the same color overlap.
2) The Second Law- Based on Maekawa's Theorem where the directions of the folds at any vertex that is the number of mountain folds, the number of valley folds will always differ by two.
3) The Third Law - Despite several attempts, a sheet will never be able to pass through a fold.
4) The Fourth Law: Around the vertices, every other angle equals 180°.

In origami, designing follows two distinct design paths namely direct design and indirect design, where the material properties play a crucial part in deciding the character of the product and origami structure, these structures are so precise and closely packed as they are impermeable to water except when sufficient pressure is created to produce structures for various applications [39]. Direct origami design tools offer diverse capabilities such as symbolic constraint solving (EOS), crease pattern editing (ORIPA), computational simulation (Kangaroo), and innovative design exploration (Crane). EOS, developed in Mathematica, is a versatile system for origami and mathematics enthusiasts. It excels in symbolic and numeric constraint solving, offering precise geometric control. EOS provides advanced origami visualization and assists in

proving theorems using mathematical methods like Grobner bases and cylindrical algebraic decomposition [40]. It also offers two folding approaches: classical and mathematical folds, making it a comprehensive tool for both origami and mathematics enthusiasts. ORIPA, the Origami Pattern Editor developed by Satoshi Takagi and Jun Mitani, is a sophisticated software tool used to create origami crease patterns [41]. It is particularly known for its ability to transform these crease patterns into folded shapes of flat origami. ORIPA's distinguishing feature lies in its capacity to discern whether a given crease pattern is foldable or not, providing valuable assistance in the design process. Additionally, it enables users to correct and refine crease patterns, making it an indispensable tool for origami artists and designers seeking precision and reliability in their creations. Kangaroo serves as a digital origami simulation tool, operating within Grasshopper as a physics engine [42]. It converts geometric model edges into spring elements with designated stiffness values. Kangaroo's algorithm maintains equilibrium by accounting for various forces, including spring stiffness, hinge-related bending forces, mesh planarity, and the strategic application of a "power-law" force. This tool facilitates the precise alignment of folded origami with target surfaces through a blend of physics and computational algorithms. Crane is an origami design software developed by MIT researchers. It's designed for digital origami modeling and focuses on computational origami design. Users can create, manipulate, and explore innovative origami forms and structures within a digital environment, allowing for rapid prototyping and precise refinement. Crane represents a leap forward in origami design, leveraging computational techniques to push the boundaries of traditional origami artistry.

Indirect origami design tools like TreeMaker, Origamizer, and OriRevo automate and optimize crease pattern creation based on user criteria, simplifying the design of intricate origami models. TreeMaker excels at reverse-engineering origami, Origamizer generates crease patterns from 3D models, and ORI-REVO aids in understanding and recreating existing designs. TreeMaker, designed by Robert Lang, is a specialized computer program for complex origami design. It utilizes a unique tree-based approach to create origami bases with specified shapes and edge lengths, which can be folded into intricate models. Additionally, TreeMaker helps explore variations of undesired patterns similar to the disk packing problem [43]. This tool is invaluable for creating preliminary prototypes by transforming 2D objects into weighted trees and calculating how to fold square paper to match this "base" structure, providing origami enthusiasts with precise design capabilities.

Demiane et al. have developed an innovative origami design software called Origamizer, that effectively dissects a model's surface mesh into discrete flat triangular sections, arranging them into a planar sheet using jointed tuckling molecules [43]. The core methodology is centered around the creation of strategically placed flat folded tucks, meticulously positioned between adjacent polygons on the provided surface. These tucks are then subjected to crimp folding, an intricate process that meticulously adjusts the angles between the sections to ensure precise conformity with the three-dimensional shape of the surface. This pioneering approach is a testament to the fusion of advanced mathematical and computational techniques in the domain of origami designs.

ORI-REVO, crafted by Jun Mitani, represents an avant-garde origami design software [44]. It harnesses intricate algorithms to facilitate the creation of intricate origami models characterized by precise crease patterns and intricate geometries. This digital medium offers a distinctive advantage through its capacity for digital prototyping, rendering it an invaluable instrument for accomplished origami artisans and pedagogical purposes alike. ORI-REVO's user-friendly interface, despite its algorithmic sophistication, renders it accessible to origami enthusiasts spanning the gamut of proficiency levels.

Miura ori structure, Miura ori lattice, hexagonal honeycombs, and cylindrical origami are among the commonly utilized crease patterns. The Miura-ori pattern is an auxetic structure that possesses single-collinearity as well as flat foldability, whose Poisson's ratio is negative (As shown in Fig. 4). The negative Poisson's ratio in Miura-ori origami is a result of the way the creases and folds are designed which results in shear deformation, When you stretch the Miura-ori pattern along one direction, the folding structure allows it to expand in the perpendicular direction, causing it to have a negative Poisson's ratio. Various other folding patterns such as zig-zag patterns have been developed based on the Miura-ori pattern.

In origami engineering, both static and hyper-static analyses are important, depending on the complexity of the origami structure and its intended application. Let's explore these analyses and how a negative Poisson's ratio can be generated in both static and hyper-static analysis.

- Static Analysis in Origami Engineering:

Static analysis in origami engineering deals with understanding the stability and shape of folded paper structures when they are not subject to external forces. It involves calculating how the folds and creases in the paper affect its behavior. Negative Poisson's ratio is not typically associated with simple static origami structures because these structures are relatively rigid and do not involve significant deformations or movements.

- Hyper-Static Analysis in Origami Engineering:

The hyper-static analysis becomes more relevant when dealing with origami structures that have flexible or movable components. This analysis focuses on understanding how these flexible parts interact and respond to external forces. To generate a negative Poisson's ratio in origami structures, engineers often design complex patterns and mechanisms that allow for specific deformations. Negative Poisson's ratio materials or structures are known as auxetic materials or auxetic structures. In origami, negative Poisson's ratio can be achieved by incorporating specific fold patterns that cause the material to expand

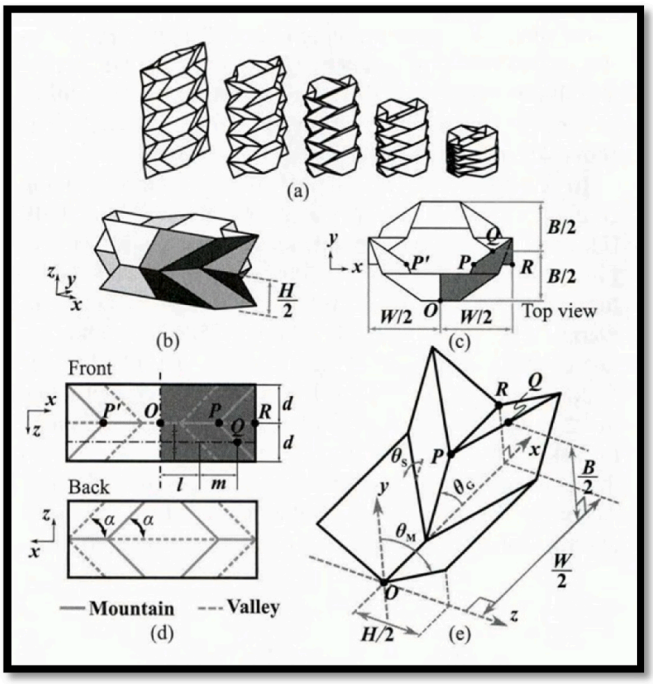


Fig. 4. (A) Folded configuration of Tachi-Miura Polyhedron (TMP) (b) A TMP cell in its folded state (c) Bird's-eye view of the Tachi-Miura Polyhedron (TMP) (d) The TMP's front and rear sheets lying flat, displaying a crease pattern composed of both mountain and valley folds (e) The folded state of the front sheet, corresponding to the shaded regions in (c) and (d). Reprint for [45] with permission. Copyright 2015, American Physical Society.

laterally when stretched longitudinally, which is the opposite behavior of typical materials (Fig. 5).

This effect can be utilized in applications like stretchable electronics, expandable medical stents, or impact-resistant materials. Achieving a negative Poisson's ratio in origami structures often involves carefully designing and optimizing the folding patterns to induce auxetic behavior. Let us consider a simple paper origami design for a better understanding.

This design is made by folding a sheet without cutting and it follows the laws of origami. The given 3D structure is auxetic in nature as it exhibits negative Poisson's ratio. The given model possesses certain degrees of freedom and degrees of redundancy. The DOF is the ability to move in a number of different directions, here in this case the degree of freedom will be 6 (x,y, z axis, Yaw, Roll, and Pitch) and the degrees of redundancy will be the limit of extension after which the model will go back to the flat state.

Traditional origami allows the transformation of the material by using Miura-Ori patterns, which are made up of similar mountain and valley fold unit cells with four-coordinated ridges (Fig. 6) [48]. Few studies have investigated the role played by design patterns and methods on structural outcomes. The findings of the study illustrated how different Miura-ori designs may affect stability and the pressure-stability correlation. Miura-ori pattern is studied based on its geometry and transitions where the creases meet faces at the vertex (Fig. 7A). The device's quick and dispersed shape transformation capabilities make it appropriate for applications such as morphing aircraft wings and kinetic structures.

According to Chen et al. when a material undergoes vertical stress where Miura-ori and water bomb unit cells might pop upwards and downwards this results in bi-stable origami unit cells deforming similarly to stiff linkages with flexible hinges [49]. The water bomb origami structure was mathematically studied by using the Kawasaki theorem (Fig. 7B). It can be seen that the reported literature mostly adapts the known crease designs, bringing innovation in the implementation, rather than the discovery of new designs. The coupling of origami with other techniques such as tensegrity developing reconfigurable tensegrity structures, modification of existing crease patterns, and the development of hybrid designs, coupling of more than one crease pattern is still at the preliminary stage and requires more attention.

A number of design patterns specific to origami, such as the Maekawa-Justin pattern [1] and Yoshimura's pattern, can be used to guide the creation of complex and mathematically precise origami structures. To determine the flat foldability of the crease origami pattern

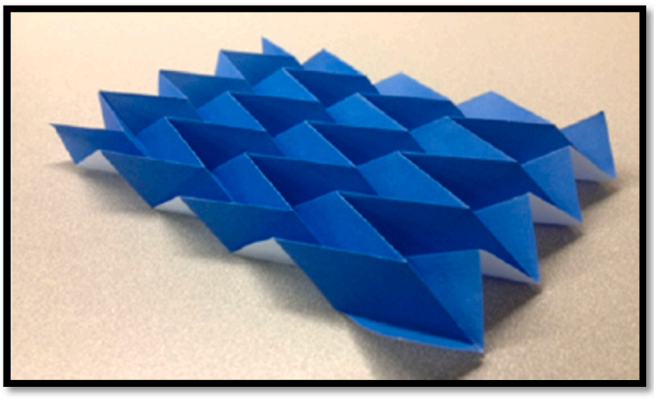


Fig. 6. An instance of a Miura-ori tessellation executed in folded paper. Reprint for [47] with permission. Copyright 2014 IOP Publishing Ltd.

(Maekawa-Justin pattern) [1] is used, at every vertex the difference between the number of mountain and valley folds is always divisible by 2 (even). Whereas, if a flat sheet of paper is folded in a series of straight lines using alternately mountain and valley folds known as the Yoshimura pattern (known as Diamond tubular structure or corrugation) [50] is created on the surface of the thin-walled cylindrical tube when it was compressed axially. The Yoshimura pattern has rigid and flat behavior and when it is folded it shows negative Poisson's (exposed to axial deformation, it expands transversely (perpendicular to the applied force). The interior vertices having six crease lines (two valleys and four mountains), offers greater foldability and a higher degree of freedom (DOF) due to their axial deformability (movement in multiple directions) as compared to Miura-pattern. Yoshimura pattern has characteristics like one unit cell consisting of a diamond that is divided from the center to create two isosceles triangles [51], the parallel diagonals in one direction are folded as valley folds, while the edges are folded as mountain folds [52]. Consequently, the folding arrangement results in the formation of a Yoshimura pattern (Fig. 8).

4. Manufacturing

Origami manufacturing is a systematic process of intricately folding paper to craft artistic items, and it extends into packaging design by utilizing custom folding techniques to provide both product protection and an appealing aesthetics. Material selection spans traditional paper

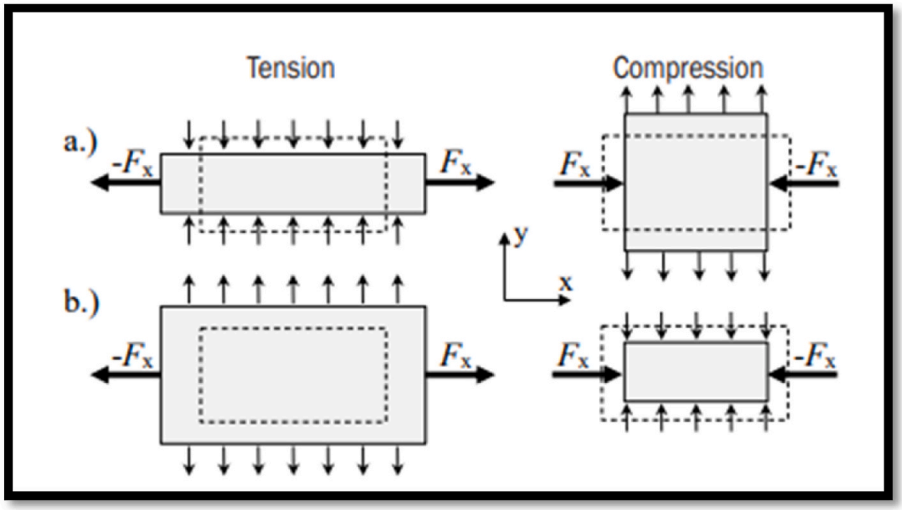
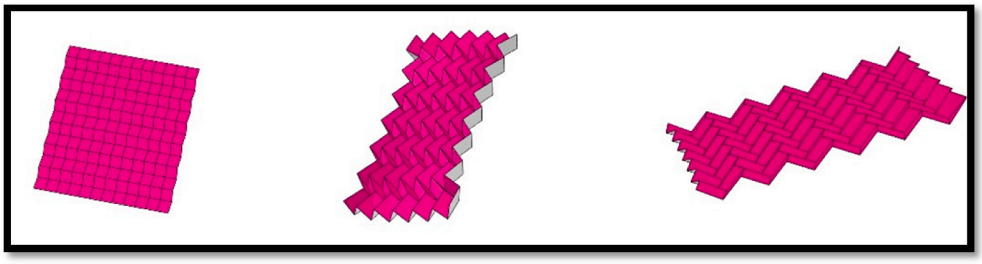


Fig. 5. (A) Behavior without auxetic properties during tensile and compressive loading (dashed lines represent the undeformed geometry). (b) Behavior with auxetic properties during tensile and compressive loading (dashed lines represent the undeformed geometry) Reprinted from Ref. [46] with permission. Copyright 2016.

A) miura ori structure:

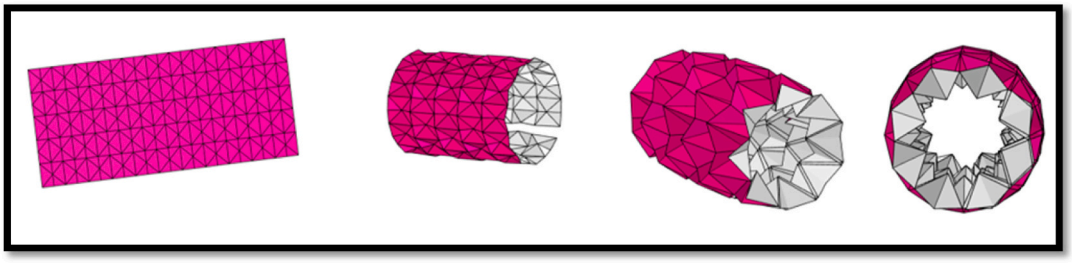
i ii iii



i)Miura ori sheet of 2D material unfolded ii) Twisted folded material in miura ori pattern iii) Miura-ori pattern.

B) Waterbomb origami:

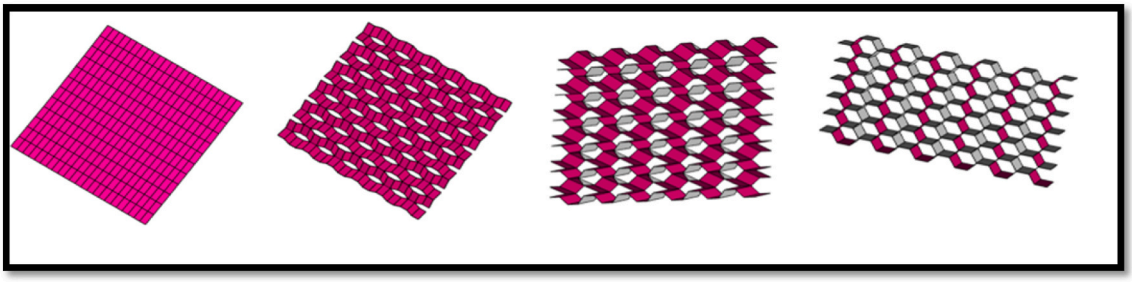
i ii iii iv



i) Plane sheet of 2D materials printed and pattern drawn. ii) Slightly folded circularly. iii) Horizontally placed in waterbomb pattern. iv) Front view of the Waterbomb tube.

C) hexagonal honeycomb structure:

i ii iii iv



i)Plane sheet of printed material. ii) -folded sheets with folded structure iii) sheet expanded and structure achieved iv) Ariel view of the hexagonal panel.

Fig. 7. Basic origami structures with various patterns.

to modern options like metals, textiles, plastics, and composites. A significant focus and extensive research have been dedicated to the evolution of origami folding techniques, aimed at establishing it as a versatile means for crafting three-dimensional components. Origami-inspired manufacturing represents an accessible approach for the fabrication of intricate three-dimensional material structures by combining electrospinning and paper-folding techniques. The production of hollow objects with thin-shell structures presents challenges from

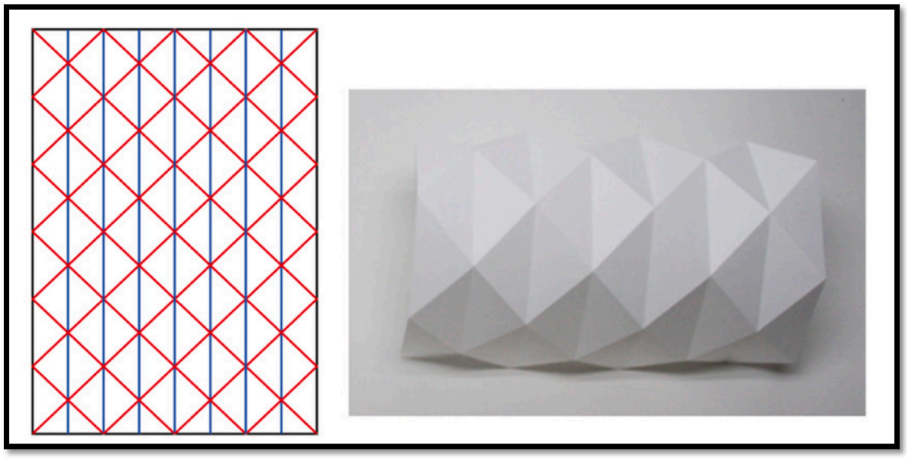


Fig. 8. Yoshimura pattern (Diamond or kite shape). Reprinted from Ref. [50] with permission from Elsevier 2017.

manufacturing processes like machining and injection molding due to inherent limitations related to internal access, while layer-based additive manufacturing processes [53], by transforming 3D models into 2D layers, effectively circumvent these constraints, establishing additive manufacturing a more appropriate option for such fabrication [54]. In the last two decades, significant advancements in additive manufacturing technologies have enabled the 3D printing of diverse materials, enabling the creation of intricate 3D shapes through the extensive design flexibility it provides. 3D as additive manufacturing [55], 3D printing lies in its capability to swiftly produce tailored components, often described as "mass customization" [56]. The evolution from 3D to 4D printing represents a significant advancement. Introducing new manufacturing possibilities by employing specialized materials like hydrogels, shape-memory polymers, or shape-memory alloys that can respond to external stimuli such as temperature, moisture, light, or mechanical forces [57,58,59,60]. The future of manufacturing origami involves the integration of advanced materials, such as shape memory polymers (SMPs) and self-healing materials, into origami structures, enabling dynamic responses to external stimuli and expanding their applications [61,62,63,64]. Additionally, advancements in nanotechnology and microfabrication techniques will enable the manufacturing of origami structures at smaller scales, opening doors in micro-robotics, medical devices, and nanoelectronics. Origami manufacturing will align with the principles of Industry 4.0, embracing smart manufacturing processes that optimize efficiency, reduce waste, and enhance quality control. The adoption of digital twin technology will enable real-time monitoring and predictive maintenance of origami structures.

5. Origami future in various fields

5.1. printing

Recent developments in materials and manufacturing techniques, such as 4D and 3D printing, have opened the path toward the growth of origami-based active structures [65,66]. Manen et al. and co-authors, lightweight 3D-printed structures were combined with stimuli-responsive material, which would be an interesting approach where such printed designs would also be able to respond to environmental changes without the use of external actuators [67]. Origami is additionally employed to inspire 4D printing in light-responsive formations, where gels, soft materials, and natural fiber composites were used as a medium on polymeric textured surfaces. With their geometrical complexity, several configurations of these textured surfaces were produced using an inkjet printer from a rubber-like material at two different thicknesses of 2 and 4 mm; its impact energy engrossing efficiency was compared to that of a textured fabric inkjet-printed sheet. After the revolution took place, it boosted the existence of origami structures and metal coatings on smart materials, which resemble properties such as material stiffness, stress ratio, and strain ratio, limiting flexibility and affecting the material properties [68]. The precise implementation of rules used for designing the solar panels was accessible for the stage in which direct production of parabolic reflectors and was feasible to create a corner cube retroreflector was combined by using 3D printing, origami, and metal covering with attachment, as well as placing mirrors into 3D printed frames and arranging these mirrors in corner cube retroreflector. When these optical elements are paired with polymer-dispersed liquid crystal films, voltage-controlled optical power management is achieved. Bhodagi et al. experimented challenging application of printing on fabrications, which was a task for 3D printing to achieve the product, but now origami can work on fabrication by using 4D printing can achieve the efficiency of the designed product using 4D micro printing, reversible, 4D bio printing related to biomedical applications [69,70]. The configuration of 3D printing parameters for the additive manufacturing of origami-inspired structures is subject to discerning adjustments based on the distinctive features of the design, the chosen material, and the exacting technical specifications inherent to the selected 3D printing machines. Experimenting with a range of geometrical and printing parameters, the vertical height of the print determines by layer height which is 0.1 mm–0.3 mm, fill percentage to control the internal densitythe of object which is 10–20%, Temperature of nozzle 210 to 225, height 15 mm, diameter is 10 mm, layer thickness 0.15 mm, PLA is commonly used materials, but other materials like PETS, ABS or flexibile filaments can also be used [71].

5.2. Spacecraft

The majority of space structures are created with a single, clear function in mind throughout their mission; some examples include applications in devices solar panels for propulsion, shields and protective equipment, antennas, and reflectors for communication and observation [72]. Currently, the deployable folded structures could not meet all the requirements of space engineering issues in designing the structures and their particular application modification. Origami with smart polymer materials having properties that can contribute to the material and increase its flexibility so that it supports the folding and unfolding mechanism.[16]Owing to their collapsibility in some structures and negative Poisson's ratio (NPR), miura-ori structures were selected as the target models the material used was made up from carbon fiber reinforced polymer composite (CFRP). [73], Domber et al. considered the dimensions of repeating elastically folded composite hinges for deployed spacecraft optics. They investigated a novel foldable

composite hinge for precision deployable spacecraft components, seeking to demonstrate that recovery of VE material is independent of storage temperature in slow time [74], whereas the electromagnetic response of a suspended patched antenna is employed to control space antennas, and the intentional usage of a reconfigurable metamaterial structure based on the high permittivity of dielectric materials results in a flexible origami in the space application framework is examined. Moreover, as the aircraft environment gets complex, a shock absorption system must adapt appropriately, acting as a protective structural deformer and space saver. Shah et al. stated that origami and kirigami-based structures that safeguard crafts from various directions are diversly used as shock absorbers, emergency shelters, spacecraft applications, solar arrays [75], and solar panels, Miura structures are used for solar sail deployment to pack the sails efficiently during launch and unfold it in space, which utilizes the pressure of sunlight for propulsion. These materials utilized are isotropic, such as aluminum and acrylic. Auxetics are NPR-containing materials like foams and microporous polymers with a strong energy-absorbing capability as well as fracture resistance [76]. Since origami compresses the physical construction, it also functions as a space saver for massive missiles, which can act as saviors.

5.3. Lithium-ion batteries

In recent years, numerous attempts have been made to develop power sources with foldable, flexible, bendable, and stretchable properties similar to lithium-ion batteries and supercapacitors. However, there are many difficulties in achieving high energy density and deformational features [77]. Origami and kirigami techniques can be utilized to create structures for batteries that surpass their areal deformability and linear deformability. The packed multi-layer structure of an origami lithium-ion battery (Fig. 9A) [78] consists of electrodes (anode and cathode), current collectors, separator, aluminum tab, copper tab, and packaging material, this structure is further divided into plane cells which are divided into smaller segments such as in parallelograms (45 °) and rectangle (90 °) by Miura folding degrees shown in (Fig. 9B) [78]. Miura folding pattern is easier to fold and unfold continuously without losing its ability to store or release energy. Miura patterns help to distribute the stress and strain in each and every section of the battery. Also these patterns help to reduce damage to its internal components. In a parallelogram, the distribution of strain is along folded edges and the corners of the battery, and in a rectangle the distribution is along the edges only, the strain distribution will depend upon the structure and design of the battery. Additionally, due to the effects of thermal expansion and contraction during battery usage and charging cycles, the strain may alter. Mechanical modeling and experimental testing that is tailored to the battery design and material specifications are needed for the investigation and characterization of the strain in origami battery structures, While Stress is a term used to describe the number of forces acting on the battery structure as a result of bending, folding, or other deformations, overstress may result in mechanical failure or battery damage. Fig. 9C and Fig. D display unfolded flattened planar structure and completely compressed arrangement of origami flexible lithium-ion battery (45 °) Miura folding pattern respectively, Fig. 9E shows the (electrochemical evaluations) [79], Electrochemical evaluation plays an important role in determining the performance and efficiency of the battery by voltage and capacity analysis, Charge-Discharge Cycling, Electrochemical Impedance Spectroscopy (EIS), Coulombic Efficiency, Aging and Degradation Analysis, Rate Capability. As shown, the location of the anode and cathode electrodes by dotted black lines, at a current

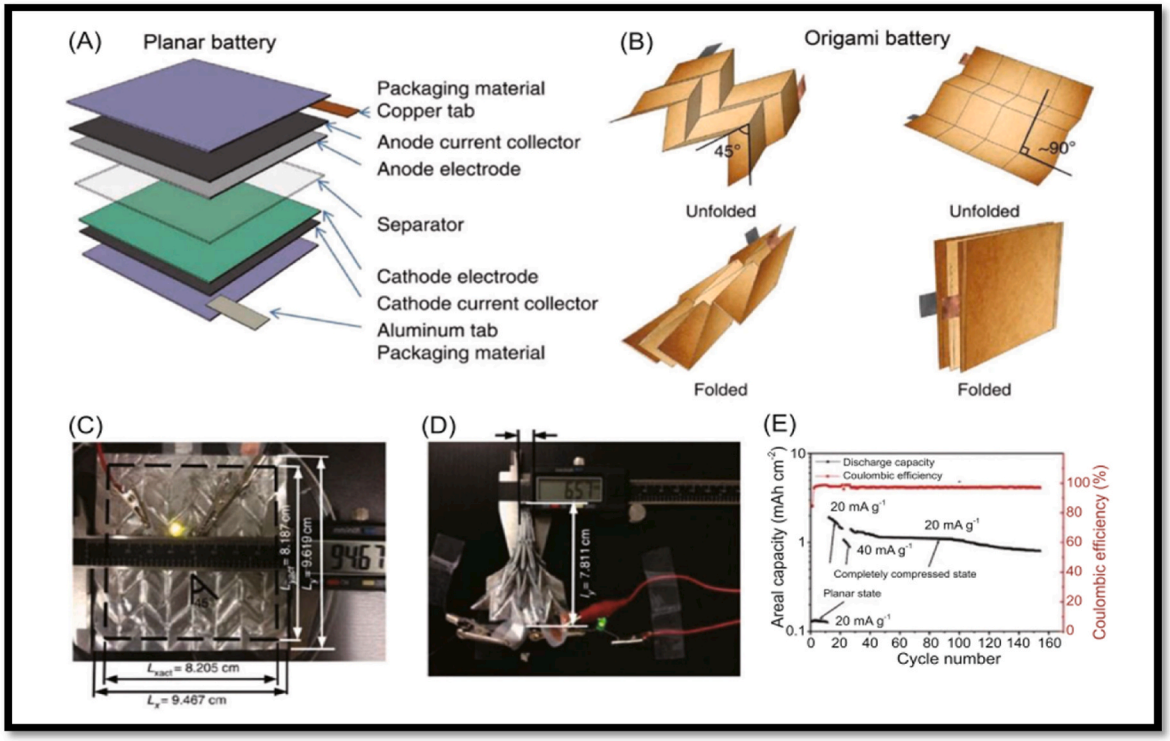


Fig. 9. Illustrating the detailed concept of lithium-ion batteries [78] (A) packed assembly of multi-layer components (B) Here are two examples of origami lithium-ion batteries using Miura folding. The lower left pictures illustrate unfolded and folded states of LIB employing (45°) Miura folding, these images demonstrate that the structure can be completely compressed in a single direction. The lower right pictures depict the unfolded and folded states of LIB employing (90°) Miura folding, these images highlight that the structure can be fully compressed in biaxial directions. (C) Images of Miura (45°) origami LIB in a completely unfolded state connected to LED (D) Images of linear deformability of Miura (45°) origami LIB in the completely unfolded state connected to a voltmeter (E) Areal capacity, Cyclability, and Coulombic efficiency of the origami FLB at the unfolded and folded states. Reprint from Ref. [78] with permission from Nature Communications, 2014.

density of 20 mAg^{-1} in unfolded flattened planar region the areal capacity was obtained by 0.2 mAhcm−2 and when it is completely compressed the areal capacity increased by 1.4–2.0 mAhcm−2, this leads to cyclic stability (charge-discharge cycle) which denotes capacity retention, good rate capacity and overall battery performance. Additionally, the areal capacity may be increased by using active materials such as LCO (lithium cobalt oxide) [78] & LTO (lithium titanate oxide) [78] to produce electrodes that are more precise and thicker, however, this change might lower the rate capacity, thicker electrodes can make it harder for the battery to blend and fold, compromising its deformability, also improving electrodes tends to achieve higher energy density. By this analysis and modeling, the origami lithium-ion batteries can achieve areal deformability and energy density capabilities. The behavior of materials under mechanical stress is influenced by mechanical properties such as linear and areal deformability. Linear deformability [78] is crucial in lithium-ion origami batteries as it enables flexibility, conformability, and structural integrity, due to linear deformability origami batteries can produce unusual form factors and have more design options for a variety of applications.

5.4. Bio-medical applications

The origami structures have found a wide range of biomedical applications, including the development of cardiac catheters, drug delivery, encapsulation, gastrointestinal microsurgery, laparoscopic operation grippers, microfluidic devices, micro grippers, sterilizers, and transcatheter grafts (Fig. 10). Researchers have been able to fabricate self-folding polymeric thin films with thickness ranging from 1 mm to 100 nm, which undergoes self-folding on the action of stimulus owing to the surface tension or differential stress. These experiments suggest that the complex polyhedral structures that cannot be fabricated using conventional techniques for the development of drug carriers can be achieved using self-folding. The fabrication of patterned locking hinges between the folding panels in such a way that on the action of a stimulus, they rotate to the appropriate place generating even complex truncated octahedra and dodecahedra structures with 14 and 12 faces, respectively.

Leong et al. produced an origami microgripper that may be activated by temperature or chemical actuation. Origami designs can start from small section folding and then grow into a huge functioning shape, allowing for a unique and less intrusive technique of treatment plans in which medical equipment moves through the body to previously unexplored locations with a similar effect of origami may be seen in various medical equipment, such as X-ray micro grippers [80]. Shuhei et al. created an origami robot that is ingestible, controlled, and biodegradable; after being ingested, the origami robot is steered to the required place to heal an effective place, remove an external substance, or administer drugs using an external magnetic field. Most medical origami devices were designed to travel earlier to reach into unreachable vivid locations to perform a procedure like catheterization or biopsy [81,82]. Upcoming origami-based biomedical improvements offer promise, including the ability to produce 3D structures, improve biocompatibility, and allow shape-shifting features [83] (Table 1).

The synthesis, design and functioning of DNA molecular machines also has gained a lot of prominence on account of the ability to design specific nanoscale patterns which can be modulated based on the complimentary pairing existing between the DNA strains and their folding. The designing as well as the processing of these DNA strains can be automated to form predictable structures and hence bestows strategy for the fabrication of nano-structures widely known as DNA origami. Nir et al. developed non-autonomous motor based on DNA-origami inspired from the bipedal walker design and studied their motion based on single-molecule fluorescence techniques. The motor fabricated followed the DNA-origami track constructed with the aid of anti-fuel and fuel strands sequentially and the usage of single-molecule fluorescence techniques as proposed can act as path-breaking technique in the fabrication of DNA-nanomachines [84].

5.5. robotics

Taking inspiration from biological systems, engineers are now investigating the integration of origami folding with smart material actuators to enable inherent actuation, thereby separating design from fabrication complexity. The inherent crease structure found in origami bodies offers the potential for compliance and the manifestation of various soft body properties. In contrast, traditional robot fabrication follows a bottom-up assembly process involving multiple low-level steps to create subsystems, often requiring manual operations and iterative processes. In contrast, natural systems achieve sophisticated designs and intricate functionalities through top-down parallel transformation methods, such as folding, resulting in elegant and efficient solutions [89]. Origami devices exhibit scalability due to decreased importance body forces (Eg., magnetism and gravity) become comparatively less influential in comparison with the surface forces (Eg, stiction, electrostatic attraction, and friction) at small scales. Their mechanical components, such as hinges and motors, become less practical at small scales, but the components of origami robots, such as flexure hinges and smart material actuators, remain effective. Origami robots offer the potential for a high specific strength, by the utilization of folded surfaces as their primary components, these robots possess a lightweight nature while still being able to achieve significant strength. Moreover, the incorporation of intricate origami or kirigami mechanisms enables the

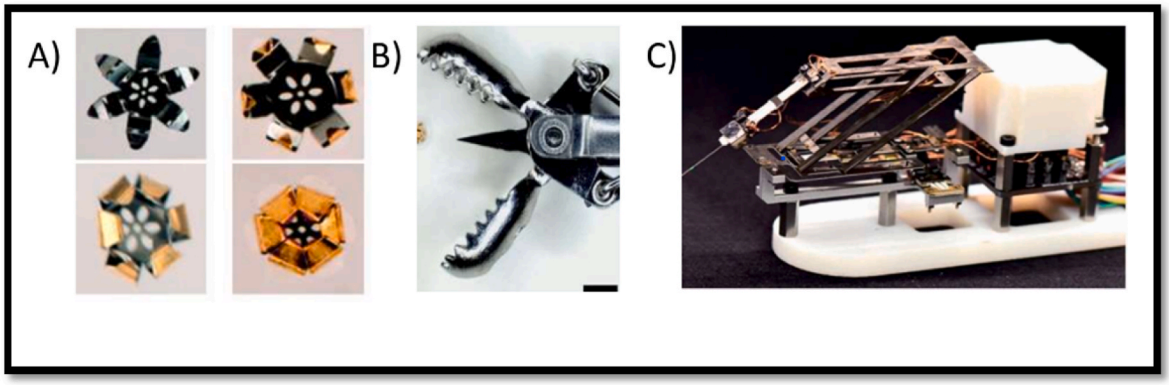


Fig. 10. Micro-origami structured equipment designed for medical applications. a) Micro star-shaped grippers reprinted with permission from Ref. [86] copyright 2010, American Chemical Society. b) Small gripper claws with a blade attached at center Reprinted with permission from Ref. [87] copyright 2013, Elsevier. c) Origami-based micro-robot is used for biomedical applications performing micro surgeries. Reprinted with permission from Ref. [88] copyright 2020, Springer Nature.

Table 1
Comparison of different SMP materials used for origami applications.

Serial Number	Material Name	Origami Application	Description	Reference
1	Shape Memory Alloys • **Thermal SMA -** Nitinols and Copper based alloy) • **Magnetic SMA-**	Actuators	Employed as reversible actuators for structural folding, An "L"-shaped SMA and inserted into a joint. Applying an electric current heated the SMAs, causing them to revert to their original shape, generating torque for easier joint rotation and achieving the desired actuation.	[23]
2	Polyetheretherketone (PEEK)	Robots	They used scientific techniques from origami to build robots that resembled worms. They chose the waterbomb base as their unit origami pattern, which is noteworthy for its ability to undergo axial contraction through radial compression.	[24]
3	Polystyrene	Actuators	They used cardboard for structure and polystyrene as the core, cut with CO2 lasers. The process pre-stressed, bonded, and heated polystyrene to about 130 °C, making it contract and fold a 2D pattern into a 3D structure. Heating time varied with complexity. They added hot melt adhesive (HMA) to enhance strength, melting during heating.	[25]
4	Polyvinyl chloride (PVC) + Aluminized Polyester	Propeller	Developed a propeller that assembles itself. They heated the structure to 110 °C, folding it into a propeller, after submerging it in water to ensure even heating. They used a magnetic field to evaluate its performance, and they created MATLAB software to create bespoke propeller designs with various angles of attack.	[26]
5	Paper + Water based ink	Paper robots	A paper robot with creases made using water-based inks folded as the solution evaporated. Cost was minimized by printing a carbon-based ink actuator using a printer. Despite its slow speed, the robot moved when voltage was applied due to differing thermal expansion coefficients of the paper and actuator.	[27]
6	poly (N-isopropyl acrylamide- co-sodium acrylate) (PNIPAM) + poly (p-methyl styrene) (PpMS) +	Robotic birds	Flapping Bird pattern: The expansion of PNIPAM allowed for customizable 3D folding when it was submerged in a room-temperature buffer solution. The process was reversible due to its temperature-responsive nature, which swelled at ambient temperature and contracted at high temperatures. A bird design, for instance, suggested potential uses as a medicine carrier when it	[28]

(*continued on next page*)

Table 1 (*continued*)

Serial Number	Material Name	Origami Application	Description	Reference
			unfurled at 55 °C and refolded at 22 °C in 10 min.	

transmission of actuation from a single source to multiple locations without the need for numerous parts and joints typically associated with traditional mechanical transmissions. This streamlined design approach minimizes complexity and enhances the efficiency of the robotic system [90]. Robotics is the advanced innovation of research and development in machines and their smart materials, where origami has served as a stepping stone in the manufacturing and design of robots, with designs that have found potential applications in robotics. These robots, which are constructed on a plane and then the assembling is done by folding, are suitable to many different typologies [91].Origami-based applications include robots that can slide, walk, bounce, and swim as human activities, boosting human-robot interactions (Fig. 11). They are conceived and constructed on a millimeter to a centimeter in size and dimensions. According to Sun et al. Origami in robots is based on dielectric elastomers which are used as joints in robots. Two stiff structural layers of liquid-soluble material were used to make a sandwich heat-sensitive layer using PVC films to generate a self-folding crease pattern on the front and back faces of the material. Global heating accelerates the robot's transition from a planar to a three-dimensional structure. The folds begin at 65 °C and take 1 min to complete [83]. The robot can walk, swim, carry, and dig by controlling the electromagnetic coils with a joystick. Concerns remain about the robot not being completely removed from the body resulting in unexpected flipping internally. The problem faced by the robot is their rigidity which increased the demands for its flexible operations have become a huge problem. Hence, the materials which were used before were replaced by using origami with smart polymers such as electrorheological materials, and electroactive materials. The working of robots is done by using dc motors, batteries, soft cables, and electricity [92]. When an electric field is applied to polymers, they start modifying their structure or size. Dielectric elastomers (DE) and ionic maps, such as ionic polymer-metal composites, are especially interesting as artificial muscles in soft simulations such as wearable robotics, walking, flying, paddling, and climbing robots (IMPS) [93]. As soft robots are in demand the increasing demand for them to act as multifunctional devices which results in using smart options such as hydrogels can be a new promising solution that can make soft material source for robots due to its outstanding features, high stretchability, high flexibility, transparency, and bio capability[24,25.]

5.6. Metastructures

5.6.1. Origami assembly of metastructures

Water droplets present a viable option for achieving origami assembly of metastructures, enabling the realization of various closed forms of polyhedral mesostructures. An alternative approach relies on the thin-film residual stresses, which undergo structural transformations based on the strain mismatch prevailing between various materials in a multilayer stack [94]. Further, the removal of the sacrificial layer induces the self-rolling of the material. This method allows for the creation of mesostructures with scroll-like, polyhedral, or tubular geometries across different material systems, including Al_2O_3, Pt, Pd–Fe–Pd, SixNy, TiO2, SiGe, ZnO, InGaAs–GaAs, and SixNy–Ag.

Another strategy involves the utilization of active materials such as SMPs, hydrogels [95], SMAs, photoactive polymers, or liquid crystal elastomers. These materials can generate spatially non-uniform strains, either out-of-plane or in-plane directions, resulting in the deformation of planar materials into preferred 3D structures and this approach offers significant flexibility to the 3D structures [96]. The final 3D configuration is typically an equilibrium state achieved by minimizing the total system energy, encompassing strain energy (membrane energy as well as bending energy for different layers present within the thin films) and work performed by external forces (e.g., capillary forces). Mechanic models define the relationships between geometric parameters, driving forces, as well as the deflection of the specimen surfaces by expressing the total energy as functions of local curvatures.

Recent studies explore the fundamental limits of this process, utilizing graphene as a structural material or in primary bending locations. Graphene's atomic-scale thickness allows for exceptionally small radii of curvature. By incorporating kirigami-inspired patterns into graphene with lateral feature sizes of approximately 2 μm, 3D configurations can be assembled under in-plane or out-of-plane loading. Mechanical stages, magnetic forces, or other external stimuli are employed to drive the assembly. Additionally, thermal activation can induce the self-tearing or peeling of graphene from a substrate, enabling folding deformations and providing a pathway for origami processes [97].

5.6.2. Applications of kirigami-inspired structures

You et al. Kirigami-inspired structures have been employed in a variety of applications, including mechanical metamaterials, electronic items, and biomedicine [98]. This research describes a simple approach for creating deformable Kirigami sculptures on shape memory polymer using a femtosecond laser. Park et al. stated that when Shock absorption was done by adding a kirigami pattern to the origami pattern resulting in the shock-absorbing and aerodynamic qualities of deformable origami structures with kirigami patterns [99]. If further research is done on design optimization for shock absorption and aerodynamics, more advanced protective structures based on understanding soft deployable structures with origami patterns may be constructed (Fig. 12) [83]. Moreover, the effect of stress absorption is likely to vary depending on the kirigami designs and future shock absorption studies will

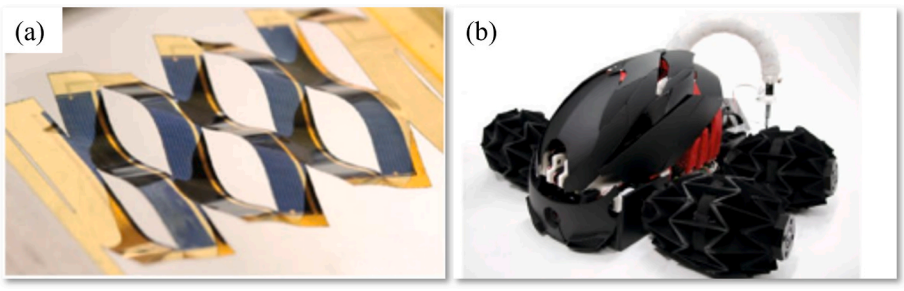


Fig. 11. Origami-Inspired robots: (a) solar tracking robot, (b) Origami wheels. (a) Reprinted with permission from [121]. Copyright 2016, Frontiers. (b) Reprinted with permission from [122]. Copyright 2015, Springer Nature.

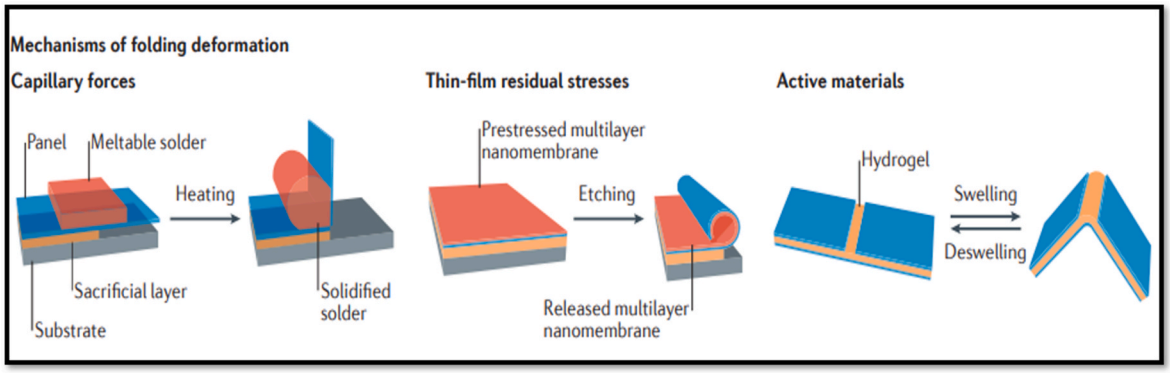


Fig. 12. Micro and nanoscale origami structures and device applications. Reproduced with permission from Ref. [101]. Copyright 2020, Wiley.

incorporate some experimental data to offer more thorough experimental findings and model predictions [100]. Table 2 consolidates the literatures available on the origami dxesigns structures and their applications (see Table 3).

6. Gap in literature and future prospects

Origami involves complex geometric design which is difficult to translate it in practical applications, origami optimization has utilized a spectrum of materials, encompassing monolithic elements, composite substances, and laminated structures, such sandwiched membrane [116]. There exist two predominant classifications within the realm of origami design for architectural structures: one pertains to autonomous self-folding mechanisms, while the other relies upon automated robotic systems or sophisticated artificial intelligence constructs [117]. The domain of self-folding origami exhibits notable parallels with the design principles underlying deployable solar panels and advanced antenna systems. In the pursuit of repeatedly foldable materials with the required foldability and stability, precision in manufacturing processes becomes pivotal, with computer-aided design tools like Treemaker and Origamizer offering practical solutions by facilitating the generation of crease patterns before folding. The application of origami-inspired principles within structural design showcases substantial promise across both contemporary practical applications and prospective research domains. These methodological approaches, deeply grounded in the art of origami, afford the capacity to synthesize biofunctionalized materials into intricately designed structures, enriched with versatile, stimuli-responsive, and self-folding attributes. In upcoming research, the focus will expand, particularly on functional shape memory materials, emphasizing bi-directional effects in substrates. The main goal is to achieve precise control in structural design. Advanced additive manufacturing systems with multi-nozzle setups will enable the blending of various materials concurrently. Additionally, the research will explore advanced computational algorithms to automate the deconstruction of 3D geometries into expanded representations, aiming for resource-efficient methods tailored to unique structural transformations. The ultimate aim is to advance innovation within this specialized domain by anticipating customized solutions based on intricate contextual variables. Furthermore, it is worth noting that all these methodologies adhere to deductive approaches, thereby yielding commendable levels of precision and operational efficiency in the attainment of desired outcomes.

7. Conclusion

In this paper, we have covered the integration of shape memory polymer (SMPs) into origami inventions as an emerging solution for contemporary challenges that supported the traditional method and helped it by replacing traditional paper with smart materials which work as the emerging solution for modern problems. Shape memory from reducing the space consumption-ability of the equipment to transforming macro to microstructures by using the folding mechanism and bending property. Among the popular crease patterns used in origami are the Miura pattern, waterbomb pattern, and Yoshimura pattern, which are types of tessellation origami. The major folding pattern used is the miura-ori crease pattern and its folding technique has

Table 2
Origami-designed medical equipment and its applications [85].

Applications	Materials	Structure	Size	Development control and its modifications.	Advantages
Heart catheterization	Biocompatible polycaprolactone or plastics	Tetrahedral origami structure.	15 mm × 30 mm × 5 mm	Imaging coils in form of origami may be placed, along with monitoring micro coils.	A flexible printed circuit board can be used to fabricate the catheter design, including the deployment mechanism and the MRI tuning and match electronics
Drug organization via programmable molecular storage space.	Graphene	_	Tens of nanometer	The graphene structure is opened and closed by external electric fields and folded by hydrogenation. As the size increases, the deployment mechanism becomes less efficient.	Graphene origami with hydrogenation assistance can capture, store, and release molecular mass.
Encapsulation microsurgery robots	Materials that degrade in water, are aluminum alloy-coated polyester, and acetone.	The device used: Micro grippers are used	17 mm	To operate the robot remotely, an external magnetic field can be used.	Swimming, delivering/carrying blocks, climbing, and digging are all tasks that can be performed. Where water can degrade all of the components except the built-in magnet.
Gastrointestinal microsurgery robot	Pig intestine and iron magnet can be used.	Micro Surgical equipment's.	15 × 30 × 5 mm	Less invasive and less costly to manufacture.	Less invasive and less costly to manufacture.

Table 3
Origami-designed systems, properties, and its applications.

System	Folding Mechanism/ Stimuli	Folding range/ Stimuli range	Crease pattern/ design	Degradability	Reversibility	Application	References
Shape memory alloys eg: nickel-titanium alloy (Nitinol)	Stimuli-Heat	40–100 °C	Design – Spring, Stents like	No(strong, Corrosion Resistant)	yes	Impact and damping applications, seismic protection applications, crack closure applications shape morphing applications, and self-deployable structures	[19,102]
Carbon Fiber reinforcement plastic	Temperature/ Mechanical stress	0-90 °	Z-folding pattern/Miura-ori	No	yes	Solar sail applications/spacecraft	[103]
Microfluidic devices	Temperature	37 °C	–	Both (yes/no)	Both (yes/ no)	Soft robotics, Drug delivery system	[104–108]
Magneto/electro-rheological fluids	Magnetic/ electric field		–	no	yes	Automotive Industry, Civil Engineering, Household Appliances, Biomedical	[104,109]
Microgrippers	Light/ Temperature -0-70 °C	62.5 °	Design: claw-like, parallel jaw-like, serrated or Notched, customized	Both yes/no	Both yes/no	Microelectronics, Microfabrication, Biomedical fields, Microsurgical applications	[105, 110–112]
polyvinyl alcohol–chitosan	Water	Intermediate Folding	–	Partial	–	biomedical Engineering, Membrane filtration	[113]
Polydimethylsiloxane	Electric	10 v	–	partial	yes	Cardiac Microtissue Transplantation	[114]
Polycaprolactone	Temperature	–	–	Yes	–	Tissue engineering, drug delivery applications	[115]

been a promising way to fold complex structures. The combination of origami and kirigami with composite materials, such as carbon fibers, Kevlar, or graphene, facilitates the creation of structures that exhibit enhanced structural integrity, strength, and lightweight characteristics, their application in industries demanding robust and high-performance structures. The utilization of carbon fiber-reinforced plastics has gained traction in applications like solar sail for spacecraft demonstrating the material's strength and lightweight properties. Microfluidic devices, enabled by materials like polydimethylsiloxane, are being applied in soft robotics and drug delivery systems. Magneto/electro-rheological fluids are finding applications in the automotive industry, civil engineering, household appliances, and biomedical fields. Many researchers have contributed to the advanced development of equipment and modified it and made it an easily accessible way for the technology. To design various types of equipment which are used for manufacturing space satellites, robotic arms, large antennae, biomedical equipment designs, and many more fields. Which are obeying the principles of mathematical equations, the chemistry of materials, and physics mechanism to study folding–unfolding theory, followed by bending theory and strain softening behavior is explained. Origami-inspired design principles offer valuable opportunities to create environmentally friendly and resource-efficient products, packaging, and architecture. Incorporating origami principles, such as efficient space utilization and collapsibility, allows for the development of innovative solutions that contribute to sustainability objectives. Through the specialized integration of materials like polycaprolactone in tissue engineering and polydimethylsiloxane in cardiac microtissue transplantation, origami-inspired approaches offer promising advancements in the field of biomedical engineering. Furthermore, the combination of materials like polyvinyl alcohol-chitosan exhibits potential in applications such as membrane filtration and the creation of microgrippers for microelectronics and microfabrication. Shape memory alloys [118,119,120], particularly nickel-titanium alloy (Nitinol), have found extensive use in impact and damping applications, seismic protection, crack closure, shape morphing, and self-deployable structures. The origami-kirigami revolution, characterized by its emergence, has ignited a proliferation of groundbreaking innovations that propel the boundaries of material implementation within foldable and cuttable structures. Proficiently leveraging a diverse range of materials, practitioners are empowered to address specific requirements and achieve remarkable advancements. The integration of functional materials, such as shape memory polymers, conductive substances, or biomaterials, imparts dynamic shape-changing properties, electrical conductivity for sensing or actuation, and holds great potential for medical applications within origami and kirigami structures. In this revolution, by mimicking folding and cutting patterns observed in nature, such as leaf folding or wing pattern, researchers can develop bio-inspired materials.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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