Futuristic Structures and Metamaterials through Origami Engineering

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Abstract. Origami, an ancient art of folding paper into structures, has inspired engineering applications in space technology a few decades ago. Due to rapid developments in manufacturing and construction technologies in recent years, scientists and engineers across the world are exploring the use of origami for applications in many other fields including mechanical, biomedical, robotics, and architecture. The property of origami-inspired structures to be light-weight, to be able to fold into compact volumes and be able to deploy into large structures can have applications for emergency shelters, deployable bridges, and may be even foldable houses or buildings. In this paper, recent developments and studies on origami-inspired futuristic structures for civil engineering and architecture are reviewed. The current state-of-the-art and the scope for development is discussed. Load-bearing capabilities of origami-based structures are analysed. Alternative uses of origami concepts to design novel systems called metamaterials, which can have applications in vibration control or blast mitigation, are discussed.

Keywords: Foldable structures · Deployable structures· Origami engineering· Load-bearing· Kinematic structures· Metamaterials· Light-weight structures.

1 Introduction

Origami, as an art of folding sheets of papers into structures, has been engaging humanity for several centuries. In recent decades, however, origami has inspired applications in engineering and technology. Some of the initial applications of origami principles were for space applications involving solar panel and antenna reflector structures that could be folded and compactly transported by spacecrafts [1, 2]. Origami concepts were also used for folding and stowing airbags for deployment during accidents of automobiles [3]. Origami also has inspired applications in robotics [4, 5].

Certain fundamental characteristics of origami, such as, foldability, deployability, and reconfigurability, find use across applications in several fields. The term *foldability* refers to the ability of a structure to reduce into a compact volume. This is of interest in efficient transport applications, from space and terrestrial applications [6] to biomedical applications involving transport of stents through blood vessels [7]. *Deployability* refers to the ability of a structure to be expanded into a large volume or area through minimal actuation. Single degree of freedom (DOF) structures, in terms of kinematic motion, are desirable as deployable structures as they can be controlled with ease. Examples, include deployable bridges [8, 9] and roofs [10]. The term *reconfigurability* refers to the ability of a structure to change its geometry significantly and transform into different shapes. Such a property is highly desirable for Transformers-type robots that can have multi-functional applications [11, 12].

In this paper, the ideas from origami engineering [13] that are relevant and applicable to the field of civil engineering are discussed. In Section 2, current state-of-the-art developments in the field of origami engineering and its challenges in respect to the applications relevant to civil engineering are discussed. Section 3 will discuss recent research related to load-bearing aspects of origami-based structures, as most civil engineering structures are of large-scale and have dominant gravity loads. In Section 4, another important application of origami concepts to develop what are called metamaterials is discussed. The paper ends with the summarizing conclusions in Section 5.

2 Origami ideas for civil engineering structures

The foldability, deployability, and reconfigurability properties of origami-based structures find immediate application as emergency shelters during disasters and for defence requirements [14]. Interestingly, origami has also inspired development of novel building systems. For example, Fig. 1(a) shows the photographs of Al-Bahr towers in UAE, which have a kinematic foldable façade system. This allows for tunable shading of sunlight allowing for more efficient indoor conditions of the building [15]. Researchers have also explored the use of origami ideas towards realizing futuristic civil engineering structures that can undergo large folding and deployment. The concepts of extending origami principles to develop foldable roof structures, buildings, and bridges were presented recently [16]. Figure 1(b) shows a schematic of a deployable roof structure that can also undergo folding by origami principles. The figure shows schematics of three partially folded states of 5%, 70%, and 97% folding, which correlate with gradual deployment of the cylindrical roof structure.

Major challenges for use of origami concepts for civil engineering structures may be attributed to (i) Translating thin sheet ideas to large-scale models, (ii) Lack of analysis and design methods, and (iii) Fabrication and construction issues. Currently, most applications of origami are being pursued at centimeter scale or smaller. Few applications that involve meter scale lengths are limited in scope as temporary structures or soft fabric-based structures. So, studies are required in extending the sheet origami concepts to rigid or semi-rigid panel versions that are stiff enough for civil engineering applications. Since, the field of origami engineering is still evolving, the methods of analysis and design are varied and may need to be developed on a case-by-case basis. Eventually, systematic procedures could be developed for suitable applications. Fabrication of origami panels at larger length-scale that are connected through hinge-type mechanisms which lead to foldable or deployable structures is yet to be explored and has received very minimal attention.

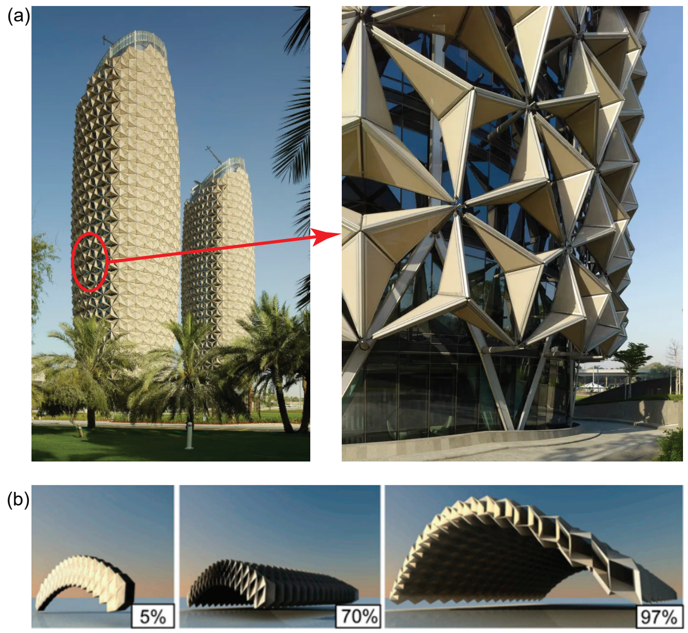

Fig. 1. Applications of origami ideas in civil engineering. (a) Origami-inspired foldable façade system of Al-Bahr towers, Abu Dhabi. Image courtesy of Christian Richters (photographer). (b) A foldable-deployable roof concept at different stages of folding using origami principles (Image is reproduced from Filipov et al. [16]).

3 Load-bearing by origami-based structures

Extending origami concepts for large-scale civil engineering structures that involve load-bearing has been attempted by a few researchers recently [17–19]. In these works, the researchers have used thick panel origami and linkage concepts [20]. That is, the panels are made out of thick materials, unlike thin sheets where thickness is negligible. Previous studies have not considered origami systems as load resisting systems for large length-scales. It is not clear whether such systems will actually be able to resists loads of magnitude that are typically encountered in large-scale structures. To investigate this issue, researchers [17] modeled thick panel origami structures using a truss-based framework and performed structural analysis under applied loads. Through simulations, it has been shown that when applied at large-scale, thick panel origami can have admissible load paths and can resist heavy loads that are typically expected [17]. Meter-scale prototypes were also constructed through wood and concrete to demonstrate the feasibility of thick panel origami for load-bearing applications [18, 19].

The Rolling Bridge at Paddington Basin of London (see Fig. 2(a),(b)) is a kinetic sculpture that mimics the foldable nature of origami-based structures. It inspires the application of origami for similar structures and with possible extension to larger scales. A schematic bridge deployment based on thick panel origami is shown in (see Fig. 2(d)) that draws similarities to the Rolling Bridge. Figures 2(c) and (d) also show the difference between using thin panels versus thick panels for the origami structure, where the thick panel version could be load-bearing in all possible configurations, unlike the thin panel structure which has a singularity at the developed or fully unfolded state.

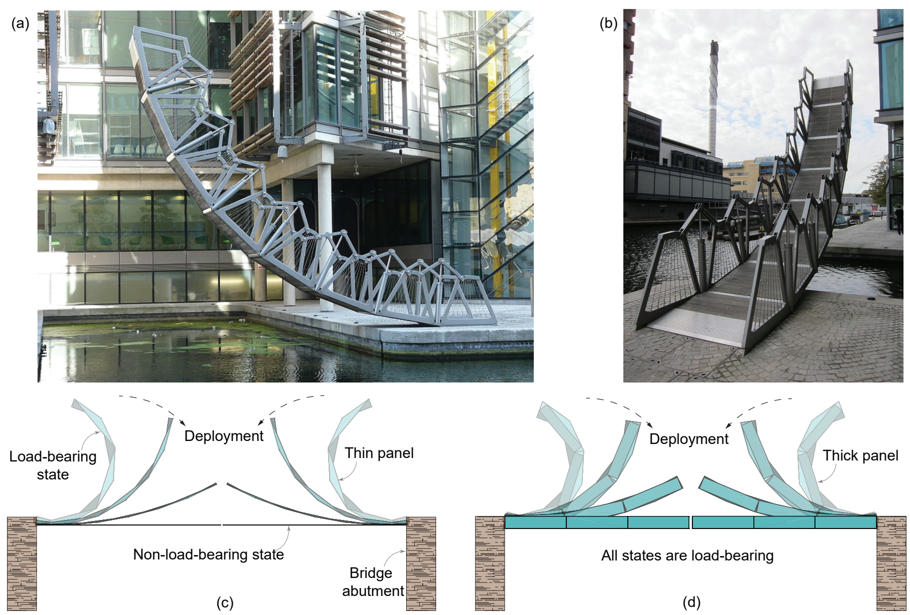

Fig. 2. Potential applications of load-bearing origami for bridges. (a) and (b) The Rolling bridge in London; image courtesy of Wikimedia Commons – Loz Pycock and Cristina Bejarano, respectively. (c) and (d) Deployable bridge concept schematics using thin and thick panel origami, respectively (Image is reproduced from Pratapa and Bellamkonda [17]).

4 Origami-based metamaterials

The geometric features of origami have also found use in the development of *metamaterials* [21] — artificially micro-structured materials with exotic properties which are primary derived from their geometry rather than their base material chemistry. The foldable nature of origami endows the resultant metamaterial with tunability of the magnitude of properties by virtue of the folded state. For example, origami-based metamaterials with tunable Poisson's ratios have been discovered [22–24] with values ranging all the way from negative infinity to positive infinity, quite contrasting to most engineering materials whose Poisson's ratio values typically lie between 0 to 0.5. Figure 3 shows a schematic of an origami metamaterial called Miura-origami (or Miura-ori) that exhibits negative Poisson's ratio (auxetic behaviour). That is as the material is stretched in one direction, it expands in the other (orthogonal) direction, unlike most conventional materials. Further, as can be observed in the figure, the metamaterial is also able to complete flat-fold into an almost zero volume state.

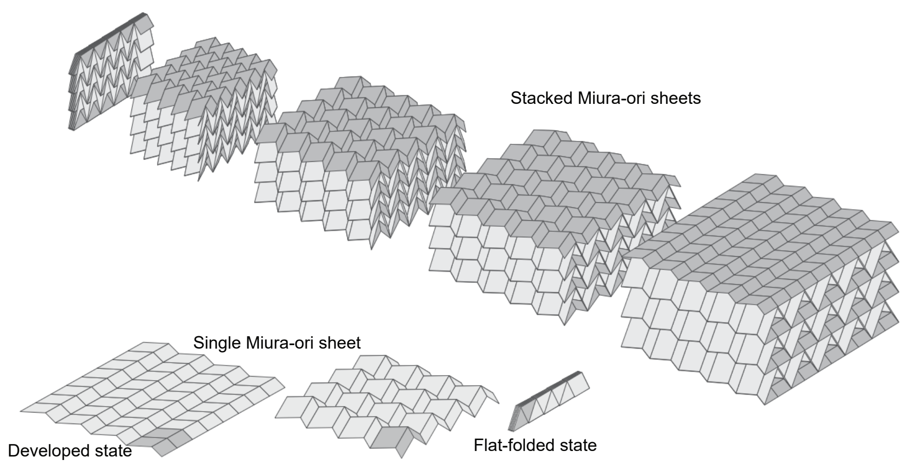

Fig. 3. Miura-origami metamaterial undergoing large volume change as it folds (Images are taken from Schenk and Guest [22] and annotated).

Origami metamaterials have also been found to display interesting wave propagation behaviour that can have applications in vibration control or blast mitigation. For example, tunable elastic frequency bandgaps were found to be possible in origami patterns [25]. Origami tessellations were found to be useful for impact mitiation by formation of rarefaction solitary waves [26]. Manufacturing and experimental realization of origami metamaterials has also been investigated by researchers by employing additive manufacturing and laser cutting techniques [27, 28].

While the above discussion highlights the potential applications of origami metamaterials, it is worthwhile to note that theoretical modeling and simulation of metamaterial behaviour has also been a prominent area of research as it could unravel new intellectual insights. Recent developments include homogenization techniques for origami metamaterials that delve into the geometric mechanics relations between stretching and bending Poisson's ratios in origami that is quite contrasting to conventional materials [29–31]. Specifically, novel homogenization frameworks using strain and curvature fields have been developed to treat origami metamaterials as an effective medium and to estimate their elastic properties [31]. Simplified reduced order models based on bars and hinges have been developed for efficient modeling and simulation of origami metamaterials [32].

5 Concluding remarks

In summary, the field of origami engineering is seeing an exponential growth in terms of researchers exploring the possibilities in several fields. There is a high potential for the usefulness of origami concepts in civil engineering to enable futuristic structures that can be multi-functional. Applications can be pursued towards foldable, deployable, and reconfigurable structures for infrastructure, buildings, as well as industrial requirements. Developments are needed in terms of design procedures and manufacturing techniques for applications at large length scales.

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