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A TUBULAR ORIGAMI STRUCTURE BASED ON A NOVEL WATERPEACE PATTERN

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Abstract. *Origami-inspired structures have been recently employed to solve several engineering problems and tubular origami structures have been of particular interest. These structures have remarkable strength-to-weight ratio, multistability and enhanced energy absorption. This paper presents a novel folding pattern, named Waterpeace pattern, for tubular origami inspired by a combination of the Waterbomb and Yoshimura patterns. A bar-hinge model is adopted and the non-rigid characteristic and multistability is attested through a finite element analysis. A comparison with the well-known Kresling pattern is provided. Potential applications as robotic arms and energy absorbers are highlighted.*

Keywords: *Origami, Origami structure, Multistability, Nonlinear mechanics*

1. INTRODUCTION

Origami-inspired systems and structures is a novel field of engineering for design of three-dimensional structures from two-dimensional elements, with unique deployment characteristics, high compactability and lightweight. Due to their adaptiveness, scalability, morphing properties and strength-to-weight ratio, origami-inspired structures have advantages in performing integrated tasks, combining considerable displacements with small and concentrate deformations.

One of the challenges of the description of origami-systems is to deal with the large number of degrees of freedom. Origami designs with repeating unit-cells, referred to as tessellated designs, are commonly employed on novel structures and materials (Meloni *et al*., 2022). Changes to the unit-cell pattern and dimensions can significantly vary the overall mechanical properties (He *et al*., 2020). Therefore, parameterization of patterns and materials can be used to tune mechanical properties of origami-inspired structures for specific application requirements (Reid *et al*., 2017).

The properties of origami-inspired structures include multistability, tunable stiffness, negative Poisson's ratio and enhanced energy absorption (Meloni *et al*., 2021; Fonseca *et al*., 2022). In special, tubular origami shapes have found numerous applications, including new types of robotic arm that utilizes their intrinsic multistability (Pagano *et al*., 2017) and improvement of structural characteristics due to their high energy absorption capability (Xiang *et al*., 2022).

This paper presents a new tubular origami that has unique properties such as nonlinear stiffness and multistability, besides it can achieve high levels of flexibility. The folding pattern of the structure is based on a novel folding pattern named Waterpeace. The presented origami structure can be either utilized as energy absorber considering its high load bearing capacity or as a type of robotic arm considering its manoeuvrability. In a quasi-static analysis, a bar-hinge model through finite element analysis is employed to investigate the multi-stable behavior of the new structure.

2. TUBULAR ORIGAMI WITH WATERPEACE PATTERN

Most-known tubular origami structures are based on Kresling, Yoshimura, Waterbomb or Miura-ori patterns (Li *et al*., 2020; Ma *et al*., 2020; Liu *et al*., 2022; Suh *et al*., 2022). These structures have been studied in a variety of applications. Tubular origami has a great energy absorption capacity and can be designed for kinetic energy absorption and impact force distribution (Yuan *et al*., 2019). Yang *et al*. (2016) show that tubular origami with Yoshimura pattern has lower peak crushing forces compared to conventional tubes. Liu *et al*. (2019) show that Miura-ori stiffened tubes have higher load bearing capacity compared to traditionally stiffened tubes. Westra *et al*. (2021) create bellows from thin-film polymers with Kresling or Yoshimura patterns and demonstrated that the folding patterns extend their fatigue life.

Tubular origami structures have also been utilized as robotic actuators (Wu *et al*., 2021). Onal *et al*., (2012) design an earthworm-like robot with a Waterbomb pattern and, alternatively, Zhang *et al*. (2021) design one with a Yoshimura pattern to achieve 3-dimensional locomotion. Kaufmann *et al*. (2022) develop a reconfigurable robotic arm with Kresling pattern.

In addition, smart materials add new perspectives for use origami-inspired structures in engineering applications (Peraza-Hernandez *et al*., 2014). The stimuli-response aspect of these materials in origami structures enables the creation of different foldable actuators based on the geometrical requirements (Rodrigues *et al*., 2017; Fonseca *et al*., 2019). Kshad *et al*. (2017) present the Miura-ori pattern as a shape memory origami design. Based on this work, Liu *et al*. (2018) measure the recovery force of a heat-activated Miura-ori structure for space-saving actuation devices. Wickeler *et al*. (2023) fabricate flexible tubes with shape memory polymers using Kresling and Yoshimura patterns. Novelino *et al*. (2020) present a magnetically responsive Kresling system to expand its shape-changing capability.

In general, the description of origami systems is a complex task due to the large number of degrees of freedom. Such description can be made by considering either kinematic or mechanical approaches. A kinematic-based description is essentially defined from the analysis of the origami geometry. Kinematic analysis can establish the definition of reduced-order models based on symmetry hypotheses that are useful to general describe origami systems with several degrees of freedom (Rodrigues and Savi, 2021).

In this paper, a new tubular origami is proposed. A novel folding pattern named Waterpeace is presented. The Waterpeace pattern consist in a modification of the traditional six-crease Waterbomb pattern (Figure 1). Basically, the modified Waterbomb unit-cell is shifted translated with a Yoshimura unit-cell in-between in a tessellation (Figure 2), giving rise to a novel tubular structure, which representative cell is highlighted in Figure 2.

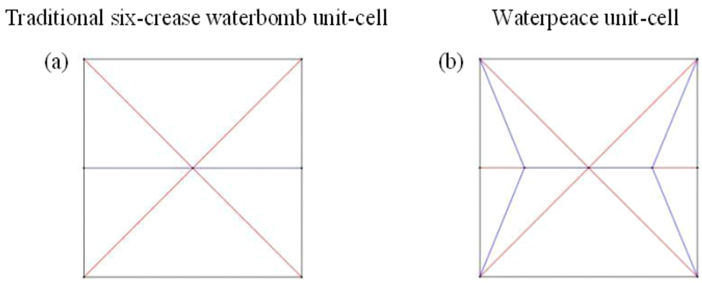

Figure 1. The difference between Waterbomb and Waterpeace. (a) A unit-cell with the traditional six-crease Waterbomb pattern. (b) A unit-cell with the Waterpeace pattern, which presents six more creases on its pattern compared to the Waterbomb.

The traditional Waterbomb tessellation give rise to a tubular origami that deploys mainly in a radial direction. However, its assemblage with the Yoshimura pattern, as in the Waterpeace pattern, creates an origami structure that can deploy in both radial and longitudinal direction, besides it presents high level of flexibility allowing an omnidirectional bending.

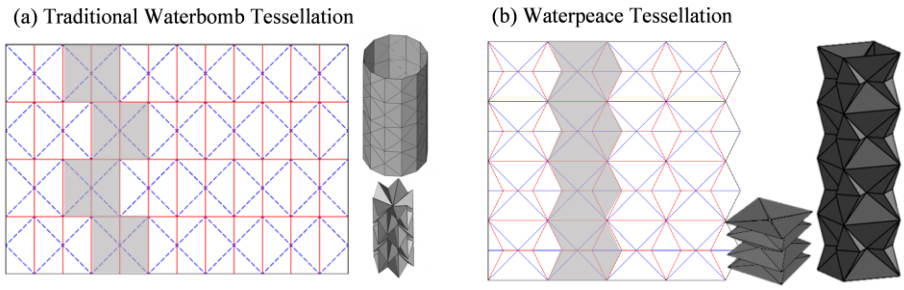

Figure 2. Origami tessellation of tubular structures. (a) Waterbomb tessellation with six unit-cells per line creates a tubular origami that deploys in the radially. (b) Waterpeace tessellation with four unit-cells per line creates a tubular origami that deploys in the longitudinal direction.

In this work, the tubular Waterpeace origami is analyzed, with focus on its multistability and potential application as energy absorber or flexible robot design. Since it is a non-rigid origami, a mechanical formulation based on a bar-hinge model is presented.

3. NUMERICAL RESULTS

In this section, numerical simulations are carried out employing the bar-hinge model for origami structures. The bar-hinge model considers the crease lines as bars with rotational spring along them. This model is an approach for understating the nonlinear mechanics of origami structures when panel deformations are not considered.

The MERLIN software (Liu and Paulino, 2017) that considers the bar-hinge model has been widely used for analysis of origami structures. This software uses a nonlinear formulation combined with a solution solver named Modified Generalized Displacement Control Method (Leon *et al*., 2014) which allows tracking of the equilibrium path even for structures displaying snap-type behavior.

Aiming to distinguish the different properties of the proposed origami with the existing ones, a comparison with the Kresling tubular origami is performed.

The Kresling pattern is a well-known cylindrical shell origami with two stable states per module. Its deployment is nonrigid, that is, the folding of the hinges itself is not enough to make the transition between the stable states. Geometrically, the Kresling pattern presents bistability with an energy barrier correlated to the height of the unit-cell. However, this statement is only valid disregarding the stiffness of the hinges. Novelino *et al*. (2020) affirm that the existence of bistability depend on the material properties of both hinges and panels since crease lines can store energy from folding.

The main idea is to perform an analysis of the novel Waterpeace pattern following the previous analysis of the Kresling pattern and highlight the differences. The bar-hinge model implemented provides information on the global behavior of the structures and how it is correlated with the energy barrier between stable states. Basically, in this analysis, the multi-stability is due to panel stretching, instead of panel bending.

In the finite element model, uniform compression forces of value *f* are applied on the top nodes of the structures. As boundary conditions, the bottom of the tubular structure is fixed on the ground in all directions (Figure 3). The basic material properties are assigned on Table 1, and they are based on the previous work of Liu and Paulino (2017).

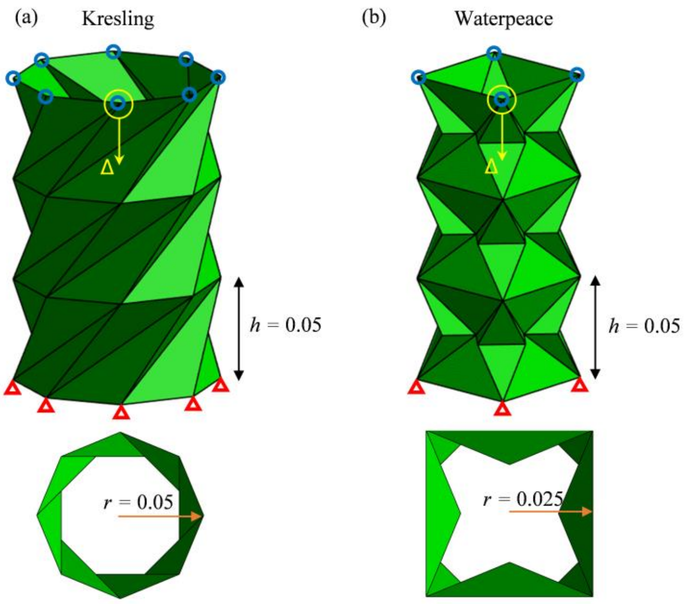

Figure 3. Geometry and boundary conditions of the numerical model. Both models, Kresling (a) and Waterpeace (b) present layers with height h = 0.05.

Table 1. Parameters considered in simulations on MERLIN software.

$\boldsymbol{k_0^F}$	$\boldsymbol{\theta_1}$	$\boldsymbol{\theta_2}$	$\boldsymbol{A_0}$
1×10^{-3}	45°	315°	1×10^{-5}
$\boldsymbol{C_0}$	$\boldsymbol{\alpha_1}$	$\boldsymbol{\alpha_2}$	$\boldsymbol{\overline{\Delta\lambda}}$
5×10^{7}	5	1	0.032

Figure 4 presents the results. In simulations, the load factor controls the magnitude of the external loads, and the displacement of the top nodes are tracked. The equilibrium path draws the downward displacement of a top node versus the value of the load factor, which can be understood as a projection of the multi-dimensional equilibrium path onto the specific plane of load and displacement. The amount of energy stored verify the non-rigid behavior.

Figure 4a and 4d suggest that the multi-stable structures have many bifurcation points and branches on the equilibrium paths and the solution solver of the finite element analysis pick one of the many branches. Figure 4b and 4e presents the stored energy on stretching (magenta) and on folding (blue), so one can conclude that the amount of energy for the deformation of the panels is more significant, comprising the non-rigid behavior of the structure. Side views of some configurations along the path are presented on the bottom of the Figure 4.

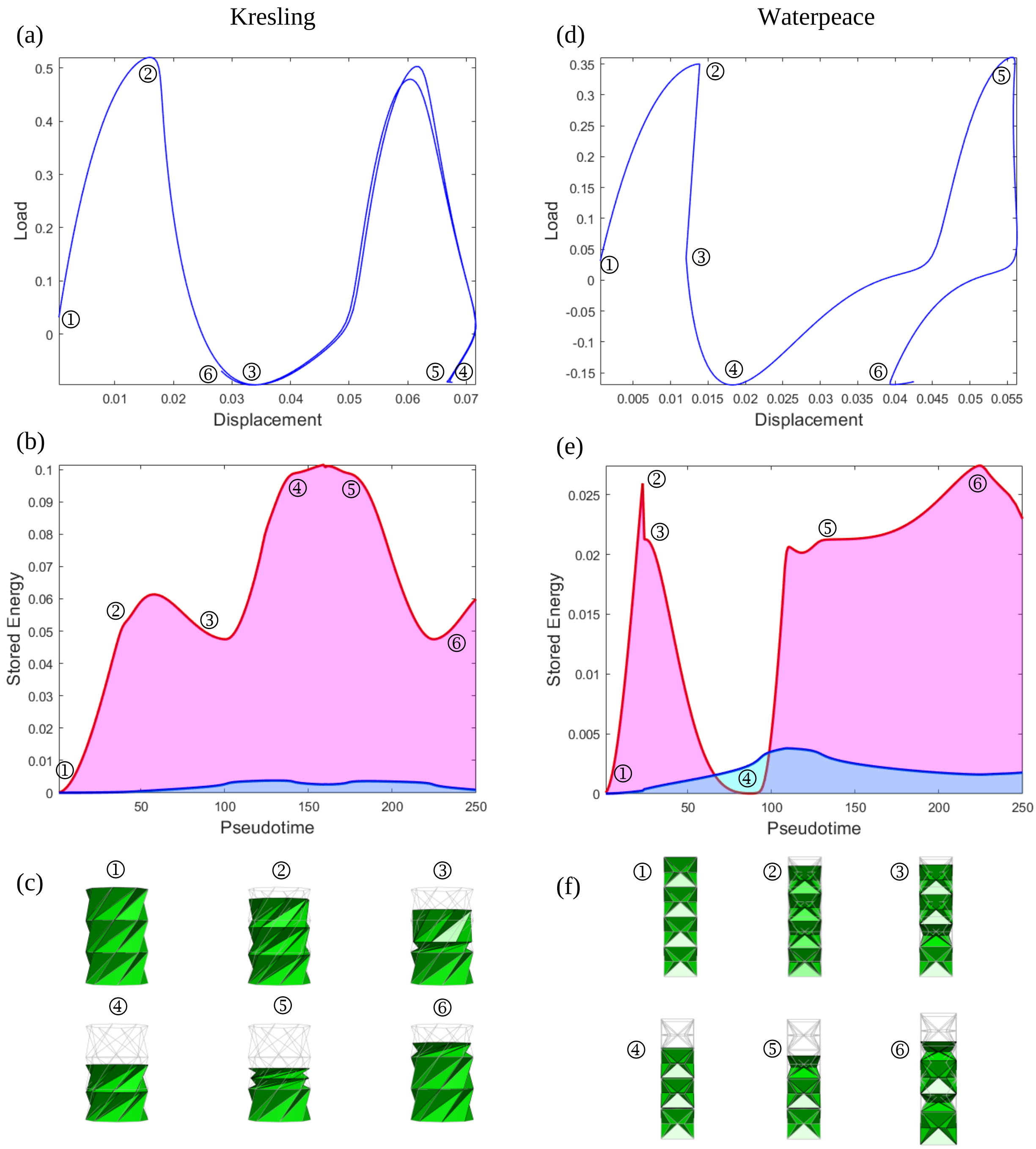

Figure 4. Finite element analysis of multistable tubular origami structures. (a) and (d) present the equilibrium path. Associated configurations (c) and (f) illustrate the global deformation of the origami at different points on the equilibrium path. (b) and (e) present the stored energy profile along the simulation process, being magenta the contribution from stretching deformation and blue the contribution from folding deformation.

Analyzing the Kresling origami, Figure 4a-c, the path from configuration (1) to (2) is the result of a uniform deformation along the structure. However, the path from configuration (2) to configuration (4) show that only the middle layer collapses. Following the path until configuration (5), the top and middle have equal chance to collapse, therefore it is related to a bifurcation point. The final configuration (6) presents only the top layer on the way to being collapsed.

Analyzing the Waterpeace origami with 4 layers, Figure 4d-f, the path from configuration (1) to (2) is the result of a uniform deformation along the structure. Suddenly, the second layer from bottom to top starts to collapse, from configuration (2) to configuration (3). This sudden change occurs as a "jump" in the equilibrium path, and this can be noted on the energy curve. As this layer collapses until configuration (4), it is noted that for the first time the energy contribution from folding overcomes the energy contribution from stretching. Continuing the equilibrium path until configuration (5), the top layer starts to collapse. However, instead of collapsing, the second layer from bottom to top, that was previously collapsed, starts to recover its height as presented in configuration (6).

In general, Figure 4 shows the comparison between these structures, and it is noted their different behavior under the same load type. Specially, the Waterpeace seems to present a non-rigid behavior at some configurations.

Given the multistability of the presented origami structure, it has potential application as new design of robotic arms. For that, its significant bending capability is presented in Figure 5. In finite element analysis, it is resulted from only two top nodes of four (Figure 3) being under compression. Figure 5a shows the nonlinear mechanical property of the structure and Figure 5b shows that the energy from folding deformation overcomes the energy from stretching. The large displacement related to a small stretching deformation is advantageous for robotic applications.

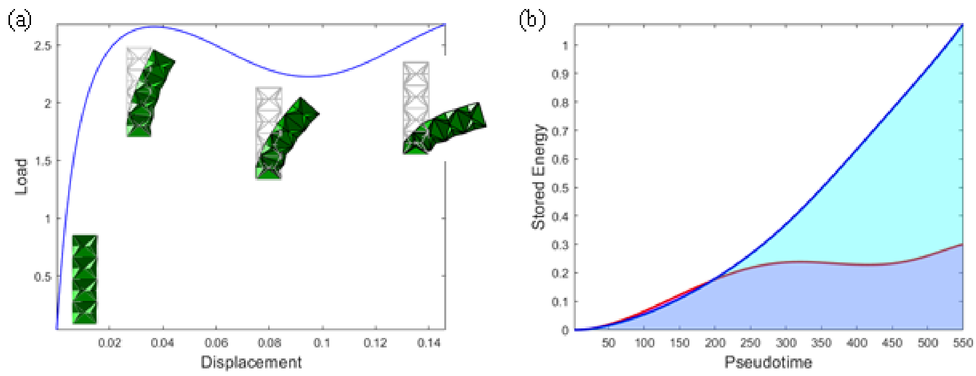

Figure 5. Bending of the Waterpeace origami.

As discussed, the multistability is related to the stiffness of origami structures. Figure 6 presents a rigid Waterpeace origami with three layers under compression. In this simulation, the stiffness k_0^F of Table 1 is substituted by 1, therefore 10^3 higher. It is noted that by increasing the stiffness, the energy from folding is much more significant than the energy from stretching. The deformation along the structure is uniform all along the simulation, thus there is not a multistable behavior. However, the nonlinear mechanic behavior is still noted in the load-displacement curve. This nonlinearity gives the structure a potential application as an energy absorber.

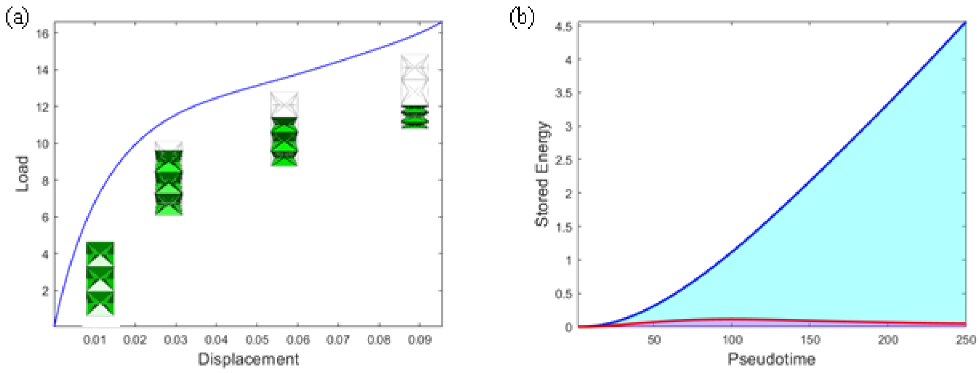

Figure 6. Compression of a rigid Waterpeace origami.

4. CONCLUSION

This paper presents a novel tubular origami which folding pattern, named Waterpeace pattern, comprises a modified Waterbomb pattern shifted translated with a Yoshimura pattern in-between. The tubular structure is non-rigid; thus, a mechanical description is performed through finite element analysis. A bar-hinge model is employed with a non-linear solver. Results show the nonlinear mechanical behavior of the structure, with potential applications as energy absorbers or new design for robotic arms. Results show how the multistability depends on the stiffness of the material. A tubular origami with a soft material presents several stable states, which is dependent of the number of layers. By increasing the stiffness, all the layers have the same behavior. Despite that difference, the nonlinear mechanical behavior is explicit. Furthermore, the bending of the structure is considered. It is shown that large displacements are achieved in bending associated with a small deformation of the panels, which is of interest in robotic applications.

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6. RESPONSIBILITY NOTICE

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