

# Mechanical behaviour of Origami based helical structure

Bin Wang, Fei Wang, Jiawei Sun, and C.Q. Chen

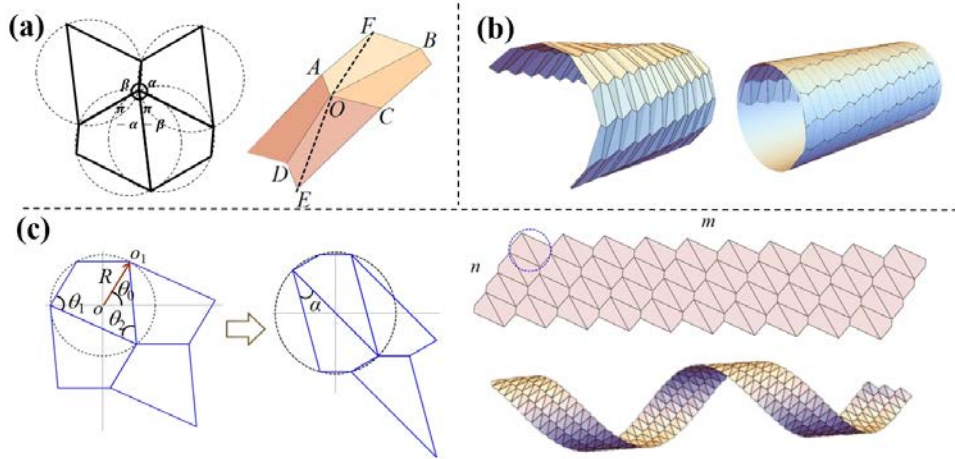
Department of Engineering Mechanics, CNMM & AML, Tsinghua University, Beijing 100084, China

Corresponding author's E-mail: chencq@tsinghua.edu.cn

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## Abstract

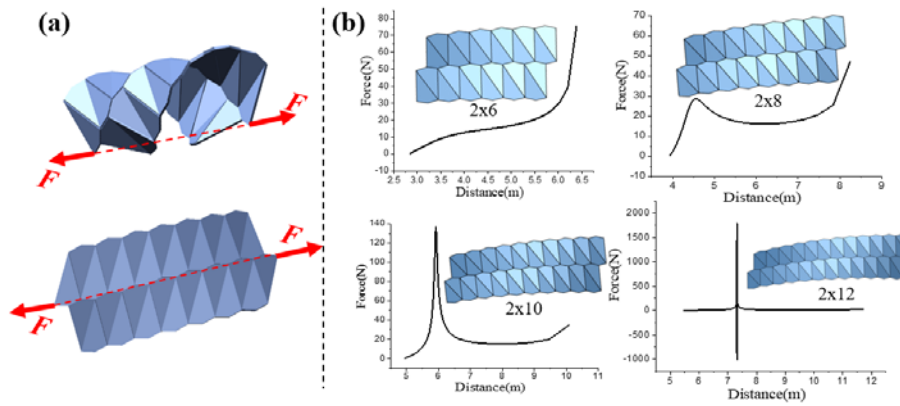
Recently, origami-based metamaterials have drawn great attention from scientists and engineers, owing to their unusual and tunable bulk properties [1]. For instance, Miura-ori based plate-like metamaterials can be auxetic and have variable stiffness [2,3]. It has already been shown that origami tessellation can be employed to map various curved surfaces [4,5]. Here, a 3D helical metamaterial is developed using cyclic quadrilateral origami unit. It has been found that its mechanical property depends on not only the unit geometry but also the tessellation pattern.



**Figure 1** (a) Origami unit based on cyclic quadrilaterals. (b) Folding tessellation on the cylinder surface, (c) Cyclic quadrilateral degrade to representative unit and corresponding tessellation

Miura-ori pattern is mostly used to form a plate-like metamaterial. However, it can only deform mainly in plane and hard to form a 3D configuration. Here, cyclic quadrilaterals are used as the base unit, with the midpoint of the public side being the rotational centre of symmetry to form an in-plane centrosymmetric configuration. (See, Fig. 1a). The base unit satisfies the flat-foldability condition automatically due to the inherent property of cyclic quadrilaterals. Unlike Miura-ori, it can be shown that all vertices locate on the same cylindrical surface and form a 3D configuration during folding with only one degree-of-freedom (Fig. 1b). It is noted that cyclic quadrilaterals when forming a base folding unit can have a number of independent parameters. For simplicity, we focus one representative configuration: we let the longest edge go through centre of circle and keep two shortest edge the same length. The corresponding

tessellation is given in Fig. 1c. With the tessellation, a helix-like structure can be developed and treated as a one-dimensional spring.



**Figure 2**(a) Typical uniaxial stretching process for helical structure, (b) Force versus distance relation of different configurations under uniaxial stretching.

In order to investigate the mechanical behaviour of the helical structure, we adopt the rigid fold assumption (i.e. all the quadrilaterals faces are rigid) and assuming that all the deformation energy is stored in the linear rotational hinges with constant stiffness. A typical uniaxial stretching process (unfolding) from the initial helix state (zero energy) to fully unfolded state is illustrated in Fig. 2a. Analytical model for the force-stretching response of the unfolding process is developed, showing that the response is a function of the geometrical parameters of the base unit. Moreover, it also depends upon the tessellation pattern, defined by the number of sides ( $n$ ) and steps ( $m$ ) defined in Fig. 3c. Figure 2b shows the model predicted force-stretching responses for 4 sets of  $(n, m)$ , i.e.,  $n = 2$  and  $m = 6, 8, 10$ , and  $12$ . It can be seen that, for a small value of  $m$  (i.e.,  $m = 6$ ), the unfolding force increases monotonically. With  $m$  increasing, however, the force first increases, followed by softening. The peak forces are in the displacement range of 4.5mm and 7.5mm. Most interestingly, the peak force increases sharply with the number of steps. In fact, the existence of a huge peak force in the force-stretching response indicates self-locking. This dependence on the tessellation has been systematically exploited and might provide new design dimension for metamaterials.

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