

Full length article

Peak stress relief of cross folding origami

Jiayao Ma^{a,b}, Degao Hou^b, Yan Chen^{a,b,*}, Zhong You^c^a Key Laboratory of Mechanism and Equipment Design of Ministry of Education, Tianjin University, Tianjin 300072, China^b School of Mechanical Engineering, Tianjin University, Tianjin 300072, China^c Department of Engineering Science, University of Oxford, Parks Road, Oxford OX1 3PJ, UK

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ABSTRACT

In this paper, cross folding of an elastic sheet, a common folding method in packaging a deployable antenna reflective membrane, was studied numerically with the aim of eliminating material failure in the sheet. The deformation, stress distribution, and peak stress of the sheet, as well as the effects of geometrical parameters on those properties were systematically investigated. Then two methods, i.e., central hole method and central slit method, were explored to reduce the peak stress caused by cross folding. A central slit parallel to the first folded crease was found to be most effective in reducing the peak stress.

1. Introduction

Deployable antenna reflectors are a typical kind of deployable structures in aerospace engineering, widely used for telecommunication, earth observation and other missions [1–6]. An antenna reflector is usually composed of a reflective membrane and a foldable ring that supports the membrane. Membrane has gained increasing popularity for two reasons: it can be easily packaged and its surface accuracy can be achieved by suitable tension upon deployment [7–11]. An antenna reflector with a diameter greater than 4 m would have to be folded into smaller dimensions in order to be fitted into a launch vehicle and subsequently deployed once it reaches its orbit [7]. Various approaches have been adopted to fold an antenna reflector. Taking the CRTS reflector [12] as an instance, the ribs are rolled inward and packed in a zig-zag way as a folded umbrella, whereas the membrane is folded in between the ribs. While this folding scheme is able to achieve a large folding ratio, it unavoidably involves two folding creases being crossed each other in the membrane, leading to the formation of a vertex in the crossed area. This phenomenon is not limited in folding the antenna reflector membranes, but a general issue when four or more folding creases are met at a vertex in origami engineering structures with initially flat or curved surfaces [13–15].

For a membrane surface made of elastic materials, such as silicone rubber based materials which are recently being explored for their capability of being deployed into a desirable shape without cable tensioning, cross folding will cause localized energy and stress/strain concentrations at folding ridges and point-like vertices [16]. The concentrations at such singularities could cause irrecoverable plastic deformations, which in turn affect the accuracy of the deployed surfaces.

Hence an in-depth understanding of the formation of vertices and ridges, their mechanical properties and influencing factors are very important for implementation of such new materials. Although bending of an elastic sheet is a thoroughly studied problem in elasticity, there is little literature related to cross folding. Therefore, the objective of this paper is to numerically model the cross folding of a flat elastic sheet in order to study the deformation, stress distribution, and peak stress of the sheet and how the geometrical parameters of the sheet influence those properties, and hence to give indications about crease designs which can be used to avoid such stress concentrations.

The layout of the paper is as follows. The geometry of the elastic sheet and the finite element modelling procedure are first presented in Section 2. Section 3 gives the deformation and stress analyses of a cross-folded sheet. Subsequently two peak-stress relief methods are proposed and analyzed in Section 4. Finally is the conclusion in Section 5 which ends the paper.

2. Geometry and finite element modelling

A square sheet of side length 100 mm was considered in this study. After several rounds of trial-and-error, the following procedure was found to naturally imitate a folding motion and to effectively cross fold a sheet. As illustrated in Fig. 1, a sheet was first folded vertically along folding path BB' (Step 1) and then horizontally along AO (Step 2), resulting in a cross formed at the center (O).

The two-step folding procedure of a sheet was controlled by 12 circular rigid bodies attached to it as shown in Fig. 1. Each rigid body was 5 mm in diameter and had a reference point assigned to it to control its movement. To achieve a natural folding motion, all reference

* Corresponding author.

E-mail address: yan_chen@tju.edu.cn (Y. Chen).

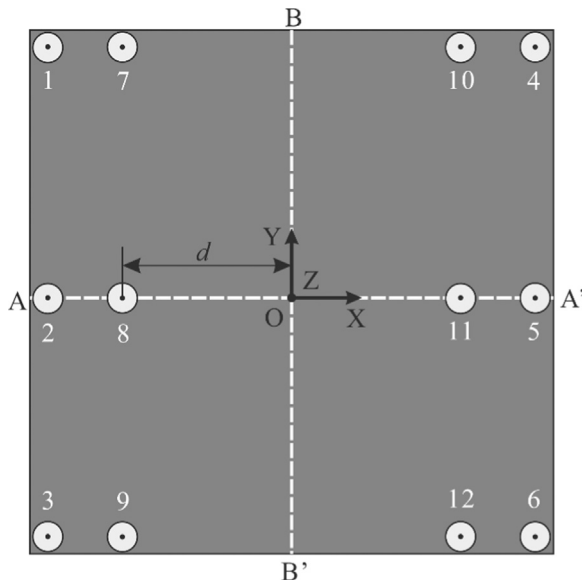


Fig. 1. Illustration of folding procedure.

points were placed at the mid surface of the sheet. Several simulations were conducted to determine the number and placement of the rigid bodies. It was found that the rigid bodies at the sides (1–6) were not enough to fold up the sheet, and hence two more columns of inner rigid bodies (7–12) with a position of d from BB' were added.

The folding motion was enabled by assigning boundary conditions to the rigid bodies [17]. Specifically, in step 1, the rigid bodies on the left-hand side and those on the right-hand side rotated about the Y-axis by 90° towards the center, but in opposite directions so that the sheet could be folded up. Accordingly, all the reference points associated with the rigid bodies were completely fixed in space except for the rotational degree of freedom about the Y-axis. And a positive value of 90° was assigned to the rigid bodies on the left-hand side, whereas a negative value of identical magnitude to those on the right-hand side. In step 2, the rigid bodies along AA' (2, 5, 8, and 11) were fixed with no translation or rotation. And the upper rigid bodies (1, 4, 7, 10) and the lower ones (3, 6, 9, 12) rotated about the Z-axis towards the center by 90° . This was also achieved by a similar setup as step 1. Notice that the expected folding mode was achieved by a proper placement of rigid bodies, without the introduction of geometric imperfection or perturbation in the sheet.

The sheet thickness t and position of the inner rigid bodies d were respectively varied between 0.1 mm and 1 mm and between 15 mm and 37.5 mm to investigate their effects on the deformation and stress of the sheet. Note that the focus of the study was how to keep the sheet in the elastic range, without considering what happened when the material went into plastic. Moreover, the peak stress in the sheets studied here was mostly within 2–3 MPa, and in this range the difference between Mises and Tresca stress was found to be small. Therefore the Mises stress was deemed suitable and adopted in all the following discussions.

The folding procedure was simulated in a quasi-static manner using commercial FEA software package Abaqus/Explicit [18]. The sheet was modelled as a 3D deformable shell and meshed with quadrilateral shell elements S4R, whereas the rigid bodies were modelled as 3D analytical rigid parts. The material was chosen to be silicone rubber with linear elastic material properties as follows: density $\rho = 930 \text{ kg/m}^3$, Young's modulus $E = 7.8 \text{ MPa}$, and Poisson's Ratio $\nu = 0.47$ [19].

Convergence tests with respect to mesh density and analysis time, respectively, were also conducted prior to the analysis and checked against two principles recommended by ABAQUS [18]: first of all, the ratio of artificial energy to internal energy was below 5% to make sure that hour-glassing effect would not significantly affect the results; and

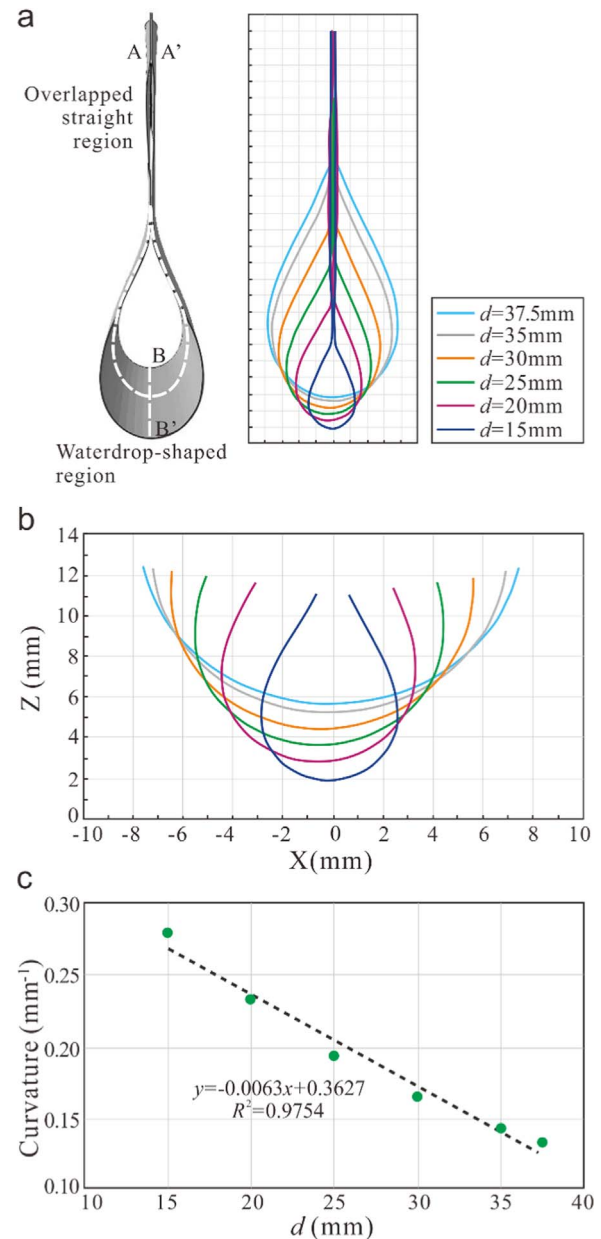


Fig. 2. (a) The deformed sheet with $d = 30 \text{ mm}$ and the profiles of AA' at varying d , (b) the waterdrop-shaped regions of AA' (Zoomed-in) at varying d , and (c) the curvature of the waterdrop-shaped region of AA' vs. d after step 1 folding.

secondly, the ratio of kinetic energy to internal energy was below 5% during most of the folding process to ensure that dynamic effect could be considered as insignificant. It was found that an element size of 1 mm and an analysis time of 0.1 s were suitable and adopted in the analysis.

3. Deformation and stress analyses

3.1. Deformation analysis

A series of sheets with $t = 0.5 \text{ mm}$ and d varying between 15 mm and 37.5 mm are investigated here. It can be seen in Fig. 2(a) that after step 1, path BB' remains straight, while path AA' is deformed into two regions: a straight one composed of two overlapped straight parts and a waterdrop-shaped one. Zoomed-in views of the waterdrop-shaped regions of the sheets are plotted in Fig. 2(b), and the largest curvature at the center of the waterdrop-shaped region is measured and plotted

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