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Geometric design and mechanical properties of cylindrical foldcore sandwich structures

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ABSTRACT

Sandwich structures with foldcores are regarded as a promising alternative to conventional honeycomb sandwich structures as lightweight structural materials. One of the proposed applications of foldcore sandwich structures is on the aircraft fuselage and the interstage of a rocket. While flat foldcore sandwich structures have been intensively studied in the literature, there lacks a general design tool to create foldcores for a given cylindrical sandwich structure and the mechanical properties of such structures have not been well investigated. In this paper, a geometrical design protocol for foldcores that will fit into the space between the external and internal walls of a given cylindrical sandwich structure is developed based on the vertex method. A parametric study on the mechanical properties of several selected cylindrical foldcore models and a honeycomb core model virtually tested in axial compression, internal pressure and radial crush using the finite element method is performed. It is shown that foldcores outperform the honeycomb core model in axial compression and radial crush but have lower radial stiffness when subjected to internal pressure. The design protocol together with the virtual test results can serve as a useful tool for researchers to design cylindrical foldcore sandwich structures for many potential applications including but not limited to aircraft fuselage, submarine shell and other pressurized cylinders.

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1. Introduction

Sandwich structures with hexagonal honeycomb cores consisting of expanded layers of aluminum foil or synthetic paper have a successful history as state of the art lightweight structures in many engineering applications due to their superior weight-specific mechanical properties. However, such structures are also known to suffer from an undesirable problem in moist environments where the closed cells tend to fill up with condensed water, leading to severe degradation of the mechanical performance over time. In the aerospace industry, for example, this drawback becomes the main reason for the field of applications of honeycomb sandwich structures being limited to secondary structures such as fairing, control surfaces, door and cabin paneling of an aircraft so that the primary structure, i.e. the fuselage shell, has not been realized with sandwich materials yet [1]. In this context, the foldcore, also known as the folded core or the origami core, made by folding thin material into a three-dimensional configuration using the principle of origami, emerges as a promising alternative to the honeycomb core. Because of the existence of open ventilation channels in foldcore sandwich structures, they do not have the moisture accumulation problem. Moreover, foldcores allow for tailored mechanical properties with a wide range of possible geometrical configurations. Therefore, there has been a surge in research interests, mainly driven by the aerospace industry, in foldcores in recent years. Two notable examples are the VeSCo fuselage concept proposed by Airbus which incorporates foldcores as a sandwich core material [2] and CELPACT, a transnational project in which the fabrication cost and impact performance of three different advanced cellular core concepts, i.e. foldedcore, selected laser melted lattice core, and closed cell core were evaluated [3].

While experimental test series remain necessary, investigations are also focused on the numerical simulations of foldcore sandwich structures using the finite element (FE) method, which has been widely adopted in the development of new composite structures as a cost-efficient research tool. As a result, a number of numerical studies of foldcore sandwich structures, such as virtual in- and out-of-plane quasi-static compression and shear tests [4–9], low- and high-velocity impact simulations [10–12], residual bending strength simulations after impact [13] and macro- and multi-scale modeling [6,11], are available in the literature. However, most foldcores used in research work are flat

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ones based on two simple Miura-based unit cell geometries with zigzag and chevron shapes [14]. Among the very limited work on non-flat foldcores is Ref. [15] in which construction and mathematical description of spiral folded structures were considered. So far, the authors are not aware of any research on computational or experimental study of cylindrical foldcore sandwich structures despite the fact that the fuselage shell is typically a cylindrical structure.

Although a flat foldcore can be bent to approximate the curvature of a cylindrical structure, bending the foldcore will cause distortion or irregular cells in its local folding pattern which might alter the mechanical performances of the core undesirably. While it is desired, designing a curved foldcore that strictly fits into the space between the external and internal walls of a cylindrical double-walled structure such as a fuselage shell poses challenges. Starting from a plane crease pattern, analyzing the relationship between its parameters and its folded 3D form, and finally adjusting the parameters to let the final folded shape conform to the cylindrical double-walled structure is a conventional approach that requires the in-depth knowledge of origami mathematics and is rather complicated. In a previous paper, we developed a 3D origami design algorithm known as the vertex method [16]. In this paper, we extended the algorithm to a design protocol of foldcores for cylindrical sandwich structures, which consists of three main steps: (a) prescribing the input forms in the x–z and y–z planes of a Cartesian system, (b) solving a non-linear equation system to obtain the design parameters according to the sandwich structure geometries, and (c) using the vertex method to acquire the final foldcore design. Based on the design protocol, we performed a parametric study on cylindrical sandwich structures with two different types of foldcores subject to axial compression, internal pressure and radial crush using the finite element method. Furthermore, the weight-specific mechanical properties of the foldcore models were compared to those of a honeycomb core model with the same density and numbers of unit cells in the circumferential and axial directions.

The layout of the paper is arranged as follows. First, the principle of the vertex method is introduced. Second, the design protocol for cylindrical foldcores is developed using one x–z plane input forms and two y–z plane input forms as examples. Third, the mechanical properties of two types of foldcores and a honeycomb core model are virtually tested and compared in the finite element analysis. Finally, a brief discussion concludes the paper.

2. The vertex method

Using the vertex method to generate a developable 3D origami structure is summarized as follows. First, specify m input points in the x–z plane of a Cartesian coordinate system, denoted by their position vectors $\boldsymbol{V}_i^x = \begin{bmatrix} x_i^x & 0 & z_i^x \end{bmatrix}^T$, $i = 1, 2, \ldots, m$, and $n+2$ input points in the y–z plane, denoted by their position vectors $\boldsymbol{V}_j^y = \begin{bmatrix} 0 & y_j^y & z_j^y \end{bmatrix}^T$, $j = 0, 1, \ldots, n+1$. Then, calculate $m \times n$ vertices $\boldsymbol{V}_{i,j}$ of the target origami structure through the following equation:

$$\boldsymbol{V}_{i,j} = \begin{bmatrix} x_{i,j} \\ y_{i,j} \\ z_{i,j} \end{bmatrix} = \boldsymbol{V}_j^y + [\boldsymbol{A}_j]\boldsymbol{V}_i^x, \quad i = 1, 2, \ldots, m; \quad j = 1, 2, \ldots, n, \tag{1}$$

where $[\boldsymbol{A}_j]$ is a 3×3 matrix given by

$$[A_j] = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 0 & (-1)^j \dfrac{\cos\ \theta_{j-1} + \ \cos\ \theta_j}{\sin(\theta_{j-1} - \theta_j)} \\ 0 & 0 & (-1)^j \dfrac{\sin\ \theta_{j-1} + \ \sin\ \theta_j}{\sin(\theta_{j-1} - \theta_j)} \end{bmatrix}, \tag{2}$$

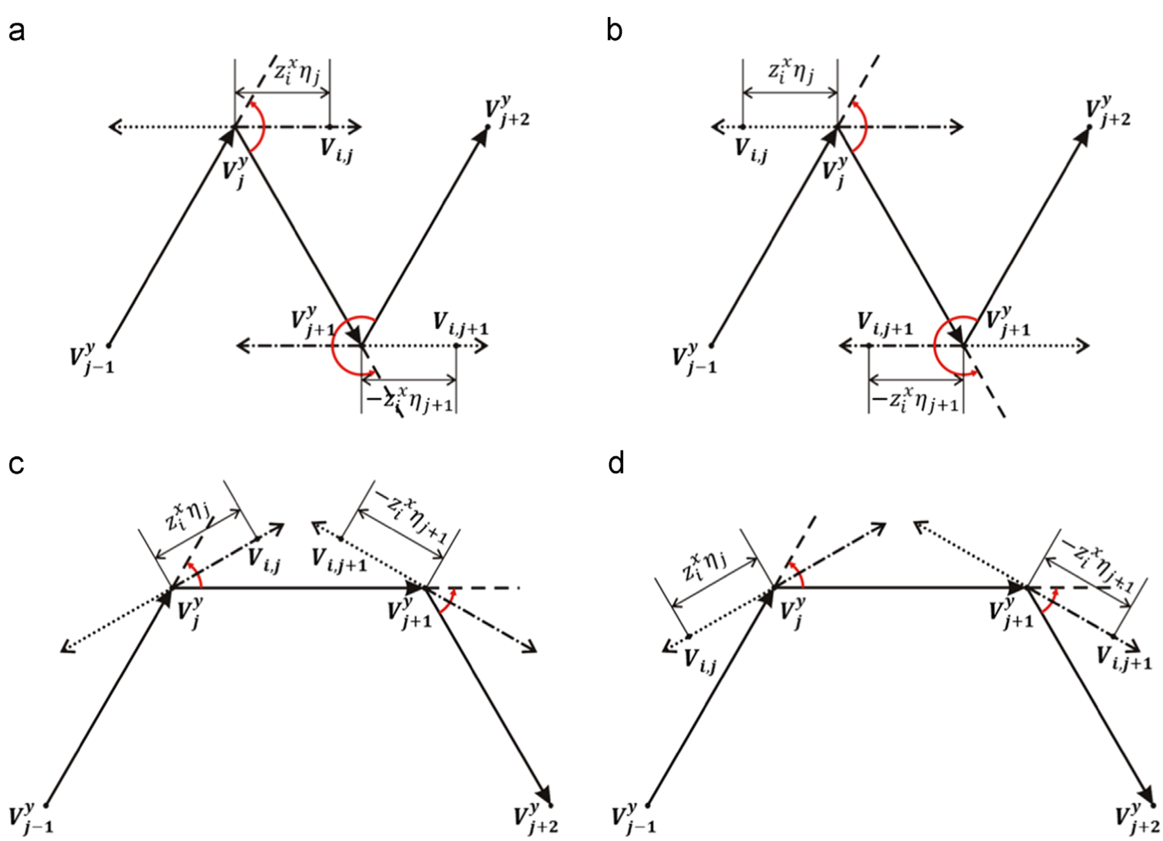

Fig. 1. Four examples for two consecutive points $\boldsymbol{V}_{i,j}$ and $\boldsymbol{V}_{i,j+1}$ in the i-th plane. (a) $z_i^x > 0$, (b) $z_i^x < 0$, (c) $z_i^x > 0$ and (d) $z_i^x < 0$

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