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Numerical study of open-top truncated pyramid folded structures with interconnected side walls against flatwise crushing

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ABSTRACT

In this study, new types of folded structures with different base shapes (i.e. triangle, square and pentagon) are proposed. Each structure is folded from a thin sheet of aluminium, with the geometry of open-top truncated pyramid and connected inclination sidewalls. The purpose of this unique geometry is to increase the crushing resistance of the folded structure while maintaining a uniform collapsing behaviour under different crushing rates as compared with other existing folded kirigami structures. Three base shapes, i.e. triangle, square and pentagon, are considered in this study. Geometric parameters are derived for these structures based on three governing parameters: top and bottom edge length and cell height. Numerical models of these structures are firstly calibrated with quasi-static crushing test data followed by dynamic crushing simulations. To evaluate the crushing performances, structural responses including peak and average crushing stress, uniformity ratio and densification strain are compared among these three structures and also with the widely studied Miura-origami structure of the same density. Superior performances of crushing are observed for the proposed open-top truncated pyramid structure with higher average stress and more uniform collapsing under various loading rates, indicating potential application as energy absorber.

1. Introduction

One of the most widely known rigid foldable origami pattern was firstly proposed by Miura [1] in 1972. Miura-type origami structure is folded from an un-broken sheet material along straight creases without twisting or stretching the structure faces. It was firstly proposed as a solar panel packaging method for space deployment [2] and recently investigated as core of sandwich structure [3–5]. Comparing with conventional sandwich structure core such as honeycomb, the open channel design of Miura-type origami core allows moisture and heat to escape, as well as the ability to be continuously fabricated from one thin sheet material [5,6]. In terms of crushing resistance, however, Miura-type origami core is not comparable to the conventional honeycomb core of similar density [7]. Furthermore, failure mode of plate buckling is also observed on Miura-type core under out-of-plane impact, leading to a non-uniform collapse. It also has a high initial peak force followed by a significant force reduction [5], a drawback for being used as a sacrificial layer for structure protection as the honeycomb core.

To increase the crushing resistance and achieve a more uniform crushing resistance of the folded structure, curved-crease foldcores were proposed [7,8]. Different from the standard Miura-type foldcore, curved-crease foldcores are folded along curves instead of segments of straight lines. Good performance of this type of foldcore is shown by comparing with the standard Miura-type, with an increase in average crushing stress and a more uniform collapsing of the core. Its crushing resistance is also comparable with honeycomb structure of the same material and density while possessing a much more uniform collapsing [9]. Crushing behaviours of Kirigami foldcore have been recently studied as well [10]. Different from Origami foldcore, the sheet of kirigami structure can be cut, stamped or punched prior to folding, therefore achieving more complex geometry and potentially increasing their crushing resistance capacity. Up to 74% rise in average crushing stress is achieved for cube strip kirigami foldcore under quasi-static crushing comparing to the standard Miura-type origami foldcore and a comparable crushing resistance to honeycomb structure [10]. However, unlike other folded structures, the best performing kirigami structures including both cube strip and diamond strip kirigami foldcores, cannot be fabricated using a single sheet material. Multiple sheet strips are required to be folded individually and placed for the fabrication of a single panel.

In many of the existing kirigami folded structures [10,11], not all vertical faces are connected with adjacent faces. Further improvements

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Fig. 1. Sample of a single unit of truncated square pyramid folded from aluminium sheet (hand folded).

in crushing resistance and energy absorption are expected for folded structure with connected vertical faces, due to more constraints provided under out-of-plane crushing. However, fully constrained cellular core could lead to a non-uniform collapsing with a high initial peak force and the crushing resistance may become very sensitive to strain rate due to the inertial stabilization provided by the fully connected sidewalls, similar to honeycomb structure [12]. An open-top truncated square pyramid folded structure (Fig. 1) with interconnected sidewalls was proposed and studied in [13,14], aiming to achieve a higher crushing resistance as well as single sheet fabrication. Its structural behaviours under out-of-plane quasi-static and dynamic crushing were investigated and compared with cube strip kirigami foldcore and aluminium foam of the same density. Good performances with high crushing resistance, low uniformity ratio (i.e. ratio of peak to average crushing stress), large densification strain and low strain rate sensitivity were observed for the proposed truncated square pyramid folded structure. Its blast mitigation capability as cladding core was also numerically studied [15,16].

Open-top truncated pyramid kirigami foldcores with different base shapes including triangle, square and pentagon are experimentally and numerically studied in this paper. Three samples are named as truncated triangular pyramid (TTP), truncated square pyramid (TSP) and truncated pentagonal pyramid (TPP). Samples of these foldcores are folded by hand and crushed under quasi-static loading condition. The crushing test data is used for the construction and calibration of the numerical model. Dynamic out-of-plane crushing are then carried out numerically for these foldcores and compared with standard Miura-type foldcore of the same density and similar dimensions. The effects of geometric parameters of the truncated pyramid foldcore such as base shape, interconnection size and shape are investigated and discussed.

2. Geometric parameters

Folding configurations of three truncated pyramid kirigami structure are shown in Fig. 2. As can be observed in Fig. 1, small folding gaps near the corners of the unit cell may exist, which are considered in the numerical models. Triangular interconnections are placed to connect all adjacent inclined sidewalls along the vertical folding creases for each unit cell. Therefore, the geometry of the folded structure is governed by three parameters only, the length of bottom and top edges, a, b and the foldcore height H. Other geometric parameters ($c, l, \alpha, \beta, \gamma, x$) marked out in Fig. 2 can be expressed by three governing parameters a, b and H as shown in Table 1. Note that A_{surf} is the surface area of a single unit cell of the foldcore, ρ_v is the volumetric density of the foldcore, and T is the thickness of the cell walls of foldcore. ρ_v is calculated using the volume of sheet material in one unit cell divided by the overall volume.

In order to form a tessellated pattern using these structures, polygons on both top and bottom planes are set to be regular polygons in this study. In other words, sides of polygons are in equal length for individual unit cell of triangle, square and pentagon truncated pyramid structures. Tessellated pattern can be easily formed without any gap for triangle and square truncated pyramid kirigami structures. As for pentagon, there is no possible way to arrange them in a plane in order to form edge-to-edge contact with all adjacent ones. Different arrangements are studied where various patterns are formed with slight gaps between adjacent regular pentagons [17]. One of the simplest tessellated pattern for pentagon is used for this study as shown in Fig. 3, where a single unit cell is marked out in dash lines including the pentagon and small gaps on both sides. Note that the base area used in calculation is the unit cell base area including the pentagon and the small gap marked out. This unit cell area selection is important for crushing behaviour of pentagonal truncated pyramid as sidewalls from adjacent units may slide towards and interact with each other. Boundary conditions for quasi-static test and numerical simulation are set accordingly.

3. Numerical model validation

3.1. Quasi-static compression test

Hand-fold samples of three structures are crushed under quasi-static compression test with a constant rate of 1 mm/min, as shown in Fig. 4. The three key governing parameters, bottom and top edge length, a, b and height H are kept same for all the three structures, where $a = 40\,mm$, $b = 20\,mm$, $H = 20\,mm$. Other parameters are shown in Table 2. Three samples have the same top and bottom edge length and height. It should be noted that 0.15 mm sheet for TTP and 0.26 mm sheet for TSP give the same relative density (or volumetric density) of 2.7% for testing. Due to the availability of aluminium sheet in Australian market, there is no aluminium (1060) sheet with proper thickness for TPP to have the same relative density as TTP and TSP for the tests. In the tests, 0.26 mm sheet is used for TPP to give the volumetric density of 1.7%. In the subsequent numerical simulation, the thicknesses for TTP, TSP and TTP are adjusted as 0.15 mm, 0.26 mm and 0.43 mm, respectively to ensure the same relative density of 2.7% and their performances are analyzed and compared.

As shown in Fig. 4(b), some slightly bent sidewalls and minor gaps can be observed near the bottom edges, caused by hand folding process. These hand folding induced imperfections are unlikely to be avoided. Advanced machining such as stamping can be developed in future to reduce the imperfections and enhance folding speed. Samples are simply supported by a steel plate with the boundary of 2 mm high to constrain the sidewall movements along the bottom edges. This is to better investigate the behaviour of a foldcore with an array of unit cells where the interaction between adjacent sidewalls shall be considered. Glue and other types of fixing between foldcore and support plate are not used.

Tensile test of the aluminium sheet used for sample fabrication is carried out to obtain its stress strain data based on ASTM E8M-04 [18]. A constant loading rate of 0.5 mm/min is applied for the aluminium strip specimen with the thickness of 0.26 mm. The full fields of displacement and strain of the specimens are measured using Digital Image Correlation (DIC-2D) techniques. The DIC image of strain field along loading direction of aluminium strip specimen at maximum strain and the obtained true stress strain curve are shown in Fig. 5.

3.2. Numerical modelling

Finite element software LS-DYNA 971 is used for numerical simulation in this paper. The folded structures are constructed using Belytschko-Tsay type shell element and placed between two rigid solid blocks. The bottom solid block is set to be a fixed rigid block, and the top block moves at a constant speed of 0.05 m/s towards the fixed base plate till around 80% crushing strain is reached for the foldcores. The 1 mm/min quasi-static crushing speed used in test is time consuming for the numerical simulation and 0.05 m/s was found sufficient to simulate accurate quasi-static loading in the numerical simulation [10]. Similar to the testing set up in Fig. 4, simple boundary condition is applied for foldcore where the base plate has a 2 mm high boundary and no glue or