International Journal of Impact Engineering 115 (2018) 94–105

Contents lists available at ScienceDirect

International Journal of Impact Engineering

journal homepage: www.elsevier.com/locate/ijimpeng

Crushing behaviours of folded kirigami structure with square dome shape

Zhejian Li, Wensu Chen*, Hong Hao*

Centre for Infrastructural Monitoring and Protection, School of Civil and Mechanical Engineering, Curtin University, Kent Street, Bentley, WA 6102, Australia

ARTICLE INFO

Keywords:
Square dome shape
Kirigami
Folded
Flatwise crushing

ABSTRACT

In this study, a new type of aluminium sandwich structure with folded square dome as core is proposed. The square dome tessellated core is folded using a single piece of aluminium sheet. Four types of folded dome structures with different base sizes and top face configurations, i.e. 10 mm closed top dome, 20 mm closed top dome, 10 mm open top dome, 20 mm open top dome are studied. A single cube strip model is numerically simulated and calibrated with the experimental results from the previous studies. Good agreement on the peak and average stress between numerical results and test data is achieved. The calibrated model is then used to simulate structural response of the proposed folded dome shape structures. The damage modes and the structural responses including average and peak stress, energy absorption, uniformity ratio and densification strain are compared among these folded structures. The proposed square dome kirigami foldcore shows good energy absorption characteristics under quasi-static loading and dynamic loading by yielding a large densification strain, a low initial peak stress and a small ratio of average stress to peak stress. In addition, unlike the existing cube strip structures, the proposed folded square dome structure shows insensitivity to the crushing speed in terms of initial peak stress and uniformity ratio. Compared with the existing tessellated kirigami foldcore of cube strip, the proposed folded square dome demonstrates a superior performance than most of Miura folded structures.

1. Introduction

Sandwich structures have been extensively studied due to the lightweight and high energy absorption capacity [1]. The performances of sandwich structures with different cores under various loading conditions have been investigated. These cores includes conventional cores, such as metallic foams [2,3], square and hexagonal honeycombs [4–6], trusses [7], lattices [8,9], corrugated [10] and some recently proposed structural forms such as functionally graded [11,12], multi-arched [13–15] and auxetic cores [16,17].

Folded core was proposed in 1972 by Miura [21] and has been intensively investigated recently. The folded core is acquired by folding sheet materials with origami patterns. Folded core can be categorized into three types: rigid foldable origami pattern, rigid foldable kirigami pattern and a variant of rigid foldable origami named curved-crease foldcores [19,20,22–24]. Examples of these three types of foldcores can be found in Fig. 1. The rigid foldable origami pattern is made from an unbroken sheet folded along creases without stretching or twisting of the panels. The rigid foldable kirigami pattern has the similar characteristics except that it is not folded from an unbroken sheet. The sheet may be cut, stamped or punched before folding. For the curved-crease foldcore, its creases are curved, which is different from the other two types where the creases are the combination of straight lines [19,20,22].

The Miura-origami foldcores have been investigated in detail. Miura foldcore is a type of rigid foldable origami pattern consisting of repeating tessellated shapes. A comprehensive review on Miura-origami foldcore was given by Heimbs [25]. Miura-type foldcore has the advantages such as continuous manufacture process and open ventilation channels which could address the issues of accumulation of humidity and heat when using conventional honeycomb as sandwich structure cores [26]. In terms of energy absorption or strength, the standard Miura-origami foldcore has inferior performance than a commercial honeycomb with comparable material and density [20]. The curved-crease foldcore was proposed and it had a higher energy-absorption capacity as compared with straight-crease foldcore or Miura-type, and slightly lower crushing resistance capacity than honeycombs in terms of average crushing stress [20]. However, the curved-crease foldcore has a more uniform failure response and a lower ratio of initial peak stress to average stress when compared with honeycomb structure.

As one of the proposed kirigami foldcores by Fathers et al. [19], cube strip has a higher average stress comparing with original Miura-type foldcore and curved-crease foldcore. A 24% increase of average stress is demonstrated as compared to the previously studied best-performing curved-crease foldcore and a 74% increase of average stress is shown over the standard Miura-type foldcore under flatwise quasi-static

---

* Corresponding authors.
E-mail addresses: wensu.chen@curtin.edu.au (W. Chen), hong.hao@curtin.edu.au (H. Hao).

https://doi.org/10.1016/j.ijimpeng.2018.01.013
Received 30 March 2017; Received in revised form 7 August 2017; Accepted 23 January 2018

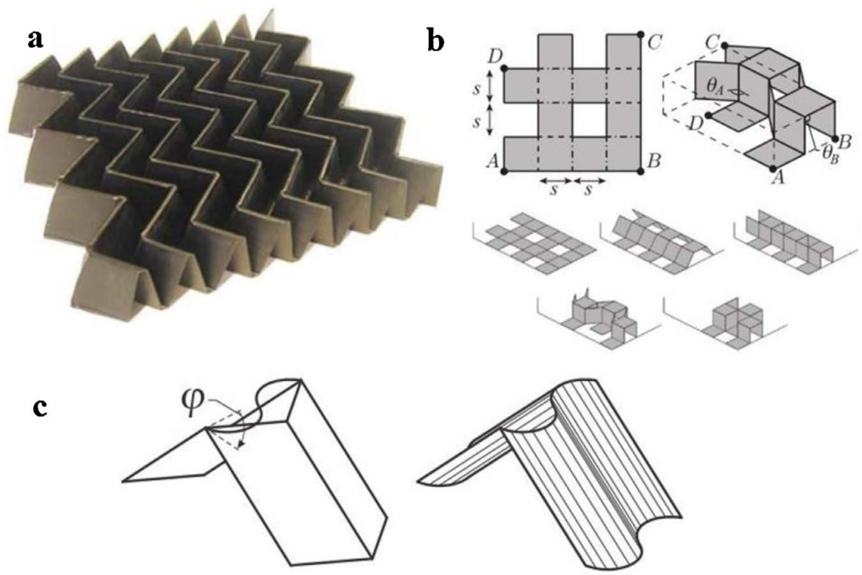

Fig. 1. Typical foldcores: (a) rigid foldable origami pattern or Miura-origami [18]; (b) rigid foldable kirigami pattern-cube foldcore [19]; (c) curved-crease origami pattern [20].

crushing. However, cube strip is folded from several sheet strips instead of one sheet, the manufacturing could be a disadvantage comparing with the Miura-type foldcores which are folded from a single sheet.

In this study, a rigid kirigami foldcore with tessellated square dome is proposed. The proposed square dome pattern is inspired by a combination of bi-directional load-self-cancelling square dome structure and the kirigami patterns by Fathers et al. [19]. Finite element analysis software LS-DYNA is employed in this study to analyse peak stress, average stress, energy absorption and densification strain of different foldcores. A numerical model of a foldcore with cube strip kirigami pattern under flatwise quasi-static crushing is firstly constructed and calibrated by comparing its generated stress–strain curves with the existing experimental data. The calibrated numerical model is then used to perform numerical simulations of the responses of the proposed foldcore structures. The proposed foldcores are compared with the cube strip kirigami structure, which has already demonstrated superior energy absorption capacity over other origami foldcores from the previous studies. In addition, various dynamic loading rates are applied on the proposed foldcores to investigate the effect of strain rate on structural response and energy absorption capacity of these foldcores.

2. Numerical model validation

In this study, finite element software LS-DYNA 971 is used for numerical simulation. Experimental data of the cube strip kirigami foldcore under quasi-static flatwise crushing by Fathers et al. [19] is used for model calibration. The accuracy and reliability of the numerical model is examined by comparing the stress–strain curves. Folding configuration of kirigami cube strip foldcore is shown in Fig. 2. Each row of cube strip is folded from a single strip of aluminium sheet and foldcore is then glued to the base plate. No connection or glue is placed between each row of cube strip. Each unit cell of cube strip foldcore consists of four 10 mm by 10 mm square faces and has a dimension of 20 mm by 10 mm by 10 mm in length, width and height, respectively. In the previous study, the strips are folded from aluminium 1100 alloy sheet with a thickness of 0.15 mm, which gives foldcore a volumetric density of $\rho_v = 3\%$.

2.1. Numerical model

A numerical model is built with one folded unit cell as shown in Fig. 3(a). To verify the numerical model, it is similar to the numerical analysis in the previous study [19]. The foldcore unit cell is modelled by using default Belytschko–Tsay type shell element, as shown in Fig. 3. An isotropic hardening material model *MAT_024 PIECEWISE LINEAR PLASTICITY is used for the material. The material properties and true plastic stress–strain data for the sample material are listed in Tables 1 and 2, respectively. The unit cell is fixed onto a rigid plate by constraining the bottom edges of the cell. The sample is then flatwise crushed till around strain $\varepsilon = 0.8$ by another rigid plate from top with a constant crushing speed of 0.05 m/s. It should be noted that computational cost for explicit simulation by using experimental quasi-static loading speed (1 mm/min) is too expensive, in this study the crushing speed of 0.05 m/s is adopted because it was found sufficient to ensure quasi-static conditions in the simulation [19]. Top rigid crushing plate is set to have only one-degree of freedom in vertical direction, which simulates flatwise crushing experiment. The self-contact of the foldcore is modelled by the keyword *CONTACT AUTOMATIC SINGLE SURFACE. The contacts between foldcore and top/bottom plates are modelled by *CONTACT AUTOMATIC NODES TO SURFACE. Friction coefficient of 0.25 is used for the contact interactions. Fig. 3(b/c/d/e) shows the numerical models of the proposed unit cells, together with the folded unit cell shown in Fig. 3(a) used for model validation.

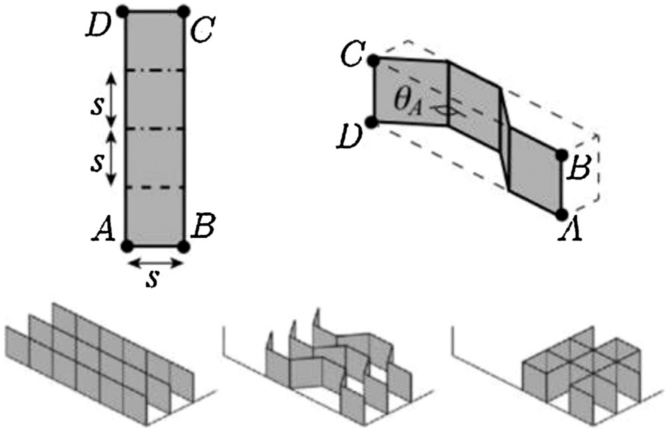

Fig. 2. Crease pattern and folded configuration of kirigami foldcore with cube strip [19].

2.2. Mesh convergence test

As an important factor for determining both the computational cost and simulation accuracy, mesh size convergence tests are carried out