Thin-Walled Structures 82 (2014) 296–310

Contents lists available at ScienceDirect

Thin-Walled Structures

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

Mechanical properties of Miura-based folded cores under quasi-static loads

Xiang Zhou [a,c,*], Hai Wang [a], Zhong You [b]

[a] School of Aeronautics and Astronautics, Shanghai Jiao Tong University, No. 800 Dongchuan Road, Shanghai 200240, China
[b] Department of Engineering Science, University of Oxford, UK
[c] School of Aeronautics and Astronautics, Shanghai Jiao Tong University, China

ARTICLE INFO

Article history:
Received 10 March 2014
Received in revised form
6 May 2014
Accepted 7 May 2014
Available online 29 May 2014

Keywords:
Miura-based folded core
Sandwich structure
Quasi-static test
Finite element method

ABSTRACT

Sandwich structures with folded cores are regarded as a promising alternative to conventional honeycomb sandwich structures in the aerospace industry. This paper presents a parametric study on the mechanical properties of a variety of Miura-based folded core models virtually tested in quasi-static compression, shear and bending using the finite element method. It is found that the folded core models with curved fold lines exhibit the best mechanical performances in compression and shear while the multiple layered models outperform the other folded core models in bending. Furthermore, the folded core models are compared to a honeycomb core model with the same density and height. In this case, it is shown that the honeycomb core has the best performance in compression while the folded cores have comparable or even better performances in the shear and bending cases. The virtual test results reported in this paper can provide researchers with a general guideline to design the most suitable folded core structure for certain applications.

1. Introduction

Composite sandwich structures, typically consisting of two thin and stiff faces separated by a thick lightweight cellular core, have many successful applications in the aerospace industry where weight-saving is the paramount design goal. In this context, honeycomb cores made of aluminum or Nomex paper are the most commonly used core type today due to their excellent weight-specific mechanical properties. However, honeycomb cores are known to suffer from an undesirable moisture accumulation problem whereby the condensed moisture is trapped inside the sealed hexagon cells leading to deterioration of the mechanical performance over time [1].

Folded cores, made by folding sheet material into a three-dimensional structure according to the principle of origami – an ancient art of paper folding – do not have the moisture accumulation problem because of the existence of open channels in such structures. Moreover, they allow for tailored mechanical properties with a wide range of possible configurations. Therefore, they emerge as a promising alternative to conventional honeycomb cores and have seen a surge in research interest from the aerospace industry in recent years. For example, in the transnational project CELPACT, the fabrication cost and impact performance of three different advanced cellular core concepts, i.e. folded core, selected laser melted lattice core, and closed cell core, were evaluated and compared [2]. Besides, the aircraft manufacturer Airbus presented a sandwich fuselage concept, VeSCo, which incorporates folded cores as a sandwich core material [3] and has made a 4.5 m^2 test assembly consisting of approximately 165,000 creases [4].

While specimen manufacturing and mechanical testing remain routine procedures, numerical analysis based on the finite element (FE) method, as an established time- and cost-efficient tool, has been widely adopted in the development of new composite structures. Besides, FE simulations can provide analysis details such as the cross-sectional stress/strain data that are usually difficult to obtain experimentally. As a result, a number of numerical studies of folded-core sandwich structures, such as virtual in- and out-of-plane quasi-static compression and shear tests [5–9], low- and high-velocity impact simulations [10–12], residual bending strength simulations after impact [13] and macro- and multi-scale modeling [7,11], are available in the literature. However, most folded cores used in research work are made of two simple Miura-based unit cell geometries with zigzag and chevron shapes [14]. So far, the authors are not aware of any research on computational or experimental studies of folded core structures beyond these two simple cases. Consequently, the mechanical properties of other folded configurations remain unexplored.

This paper presents a parametric study on folded cores with different geometric parameters based on the standard Miura folding pattern [15] and its variation forms subject to out-of-plane

* Corresponding author at: School of Aeronautics and Astronautics, Shanghai Jiao Tong University, China. Tel. +86 21 34207538.
E-mail address: xiangzhou@sjtu.edu.cn (X. Zhou).

http://dx.doi.org/10.1016/j.tws.2014.05.001
0263-8231/

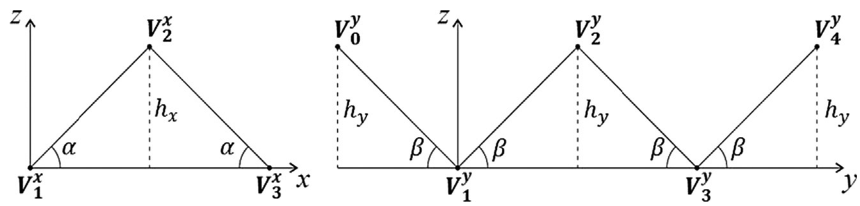

Fig. 1. The input points in the x–z and y–z planes used to generate the unit cell models UM11–UM18.

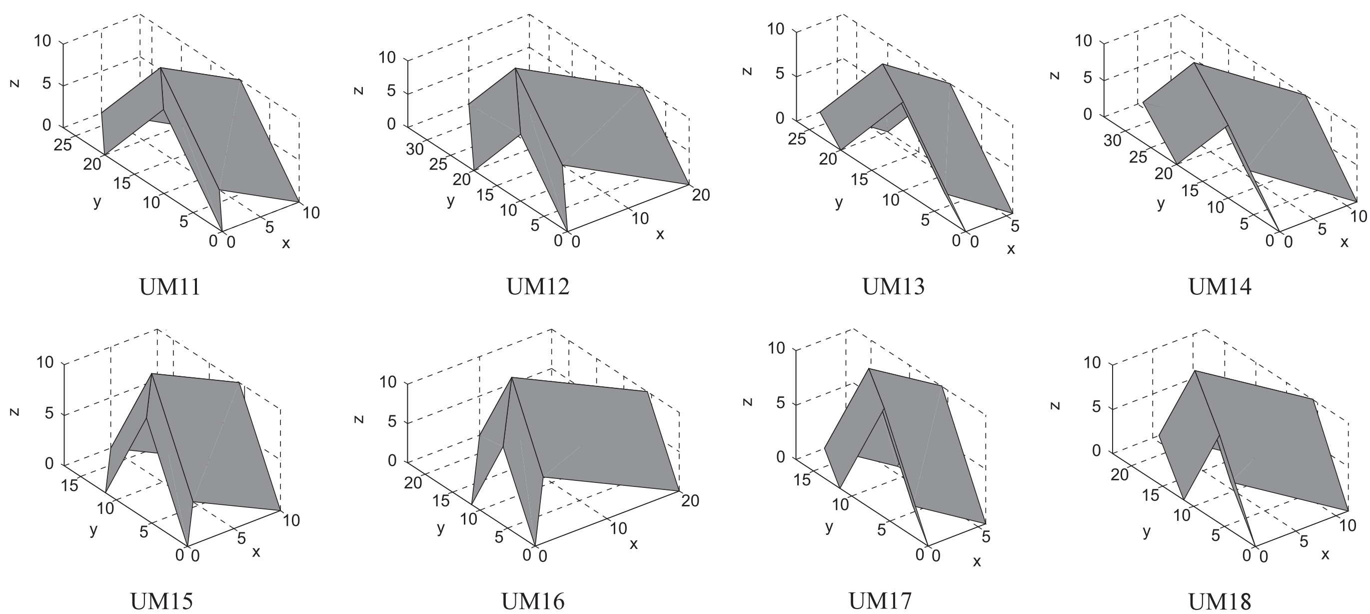

Fig. 2. Unit cell models UM11–UM18.

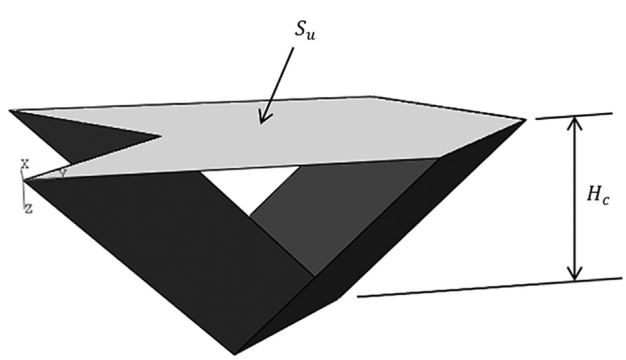

Fig. 3. Definition of the base area S_u and the core height H_c of a unit cell.

Table 1
The geometric properties of models M11–M18.

Model	α [rad]	h_x [mm]	β [rad]	h_y [mm]	H_c [mm]	S_u [mm^2]	t_m [mm]
M11	$\pi/4$	5	$\pi/4$	10	10	200	0.25
M12	$\pi/4$	10	$\pi/4$	10	10	400	0.25
M13	$\pi/3$	5	$\pi/4$	10	10	115.47	0.1768
M14	$\pi/3$	10	$\pi/4$	10	10	230.94	0.1768
M15	$\pi/4$	5	$\pi/3$	10	10	115.47	0.1768
M16	$\pi/4$	10	$\pi/3$	10	10	230.94	0.1768
M17	$\pi/3$	5	$\pi/3$	10	10	66.67	0.125
M18	$\pi/3$	10	$\pi/3$	10	10	133.33	0.125

Table 2
The parameters of the material model.

Material	ρ_m [kg/m^3]	E [GPa]	σ_y [GPa]	σ_{uts} [GPa]	ν
5052-O Al	2690	69.6	65.5	193	0.33

compression, in-plane shear and bending using the finite element method. To facilitate the parametric modeling, a new origami geometric design approach, known as the vertex method [16], is used to generate the various folded core models in this study. Furthermore, the weight-specific mechanical properties of the folded core models were compared to those of a honeycomb model with the same density.

The layout of the paper is arranged as follows. First, the mechanical behaviors of eight folded core models with the standard Miura origami folding pattern are simulated and compared. Second, the eight folded core models with curved fold lines are virtually tested. Third, a further two folded core models with multiple layers are considered. Fourth, the mechanical performances of the folded core models are compared with those of a honeycomb core model. Finally, a brief discussion concludes the paper.

2. Standard Miura folded cores

2.1. Geometric models

Making use of a set of geometric parameters to define the folded configuration of a unit cell is a commonly employed modeling