Theoretical and Applied Mechanics Letters 6 (2016) 54–59

Contents lists available at ScienceDirect

Theoretical and Applied Mechanics Letters

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

Letter

Performance enhancement of sandwich panels with honeycomb–corrugation hybrid core

Bin Han [a,b,c], Wenbin Wang [b], Zhijia Zhang [b,c], Qiancheng Zhang [b,c], Feng Jin [b,c], Tianjian Lu [b,c,*]

[a] *School of Mechanical Engineering, Xi'an Jiaotong University, Xi'an 710049, China*
[b] *MOE Key Laboratory for Multifunctional Materials and Structures, Xi'an Jiaotong University, Xi'an 710049, China*
[c] *State Key Laboratory for Mechanical Structure Strength and Vibration, Xi'an Jiaotong University, Xi'an 710049, China*

HIGHLIGHTS

- Performance of a honeycomb–corrugated hybrid sandwich subjected to out-of-plane compression, transverse shear, and three-point bending is evaluated.
- The strength and energy absorption of the sandwich are dramatically enhanced.
- The enhancement is attributed to the positive interaction effects of corrugated plates and honeycomb cell walls on mutual deformation constraints.

ARTICLE INFO

Article history:
Received 29 September 2015
Received in revised form
30 December 2015
Accepted 2 January 2016
Available online 16 January 2016
*This article belongs to the Solid Mechanics

Keywords:
Honeycomb–corrugation
Compression
Shear
Bending
Performance enhancement

ABSTRACT

The concept of combining metallic honeycomb with folded thin metallic sheets (corrugation) to construct a novel core type for lightweight sandwich structures is proposed. The honeycomb–corrugation hybrid core is manufactured by filling the interstices of aluminum corrugations with precision-cut trapezoidal aluminum honeycomb blocks, bonded together using epoxy glue. The performance of such hybrid-cored sandwich panels subjected to out-of-plane compression, transverse shear, and three-point bending is investigated, both experimentally and numerically. The strength and energy absorption of the sandwich are dramatically enhanced, compared to those of a sandwich with either empty corrugation or honeycomb core. The enhancement is induced by the beneficial interaction effects of honeycomb blocks and folded panels on improved buckling resistance as well as altered crushing modes at large plastic deformation. The present approach provides an effective method to further improve the mechanical properties of conventional honeycomb-cored sandwich constructions with low relative densities.

Honeycombs are available in a wide range of base materials, from beeswax and propolis (a kind of plant resin), paper, metal, ceramic to composite [1]. Especially, due to their high stiffness, strength, and energy absorption as well as great saving in weight, hexagonal honeycombs fabricated from aluminum (Al) alloys by an in-plane expansion process with two of the six cell walls having double thickness are widely employed in aerospace and other industries. The mechanical response of hexagonal honeycombs under out-of-plane compression and shear has been extensively studied, both experimentally and theoretically [2–6]. In out-of-plane compression, these honeycombs exhibit a stress peak followed by a series of stress oscillations associated with progressive formation of plastic folds in the cell walls. Most experimental studies about honeycombs are restricted to low relative density ($\bar{\rho} \leq 0.03$), as debonding of honeycombs from the faceplates has been observed at higher relative densities. This deficiency limits the load-bearing and energy absorbing capability of traditional honeycombs for heavy-duty applications.

Like honeycombs, corrugations (folded plates) also have fairly high specific stiffness and specific strength. Unlike honeycombs, however, the energy absorption capacity of corrugations is typically low. Under quasi-static compression, for instance, a metallic corrugated sandwich core deforms by stretching of its struts (core webs) and collapses by Euler or plastic buckling, with a sharp softening after the peak load. Metallic corrugations are thus less

* Corresponding author at: MOE Key Laboratory for Multifunctional Materials and Structures, Xi'an Jiaotong University, Xi'an 710049, China.
E-mail address: tjlu@mail.xjtu.edu.cn (T. Lu).

http://dx.doi.org/10.1016/j.taml.2016.01.001

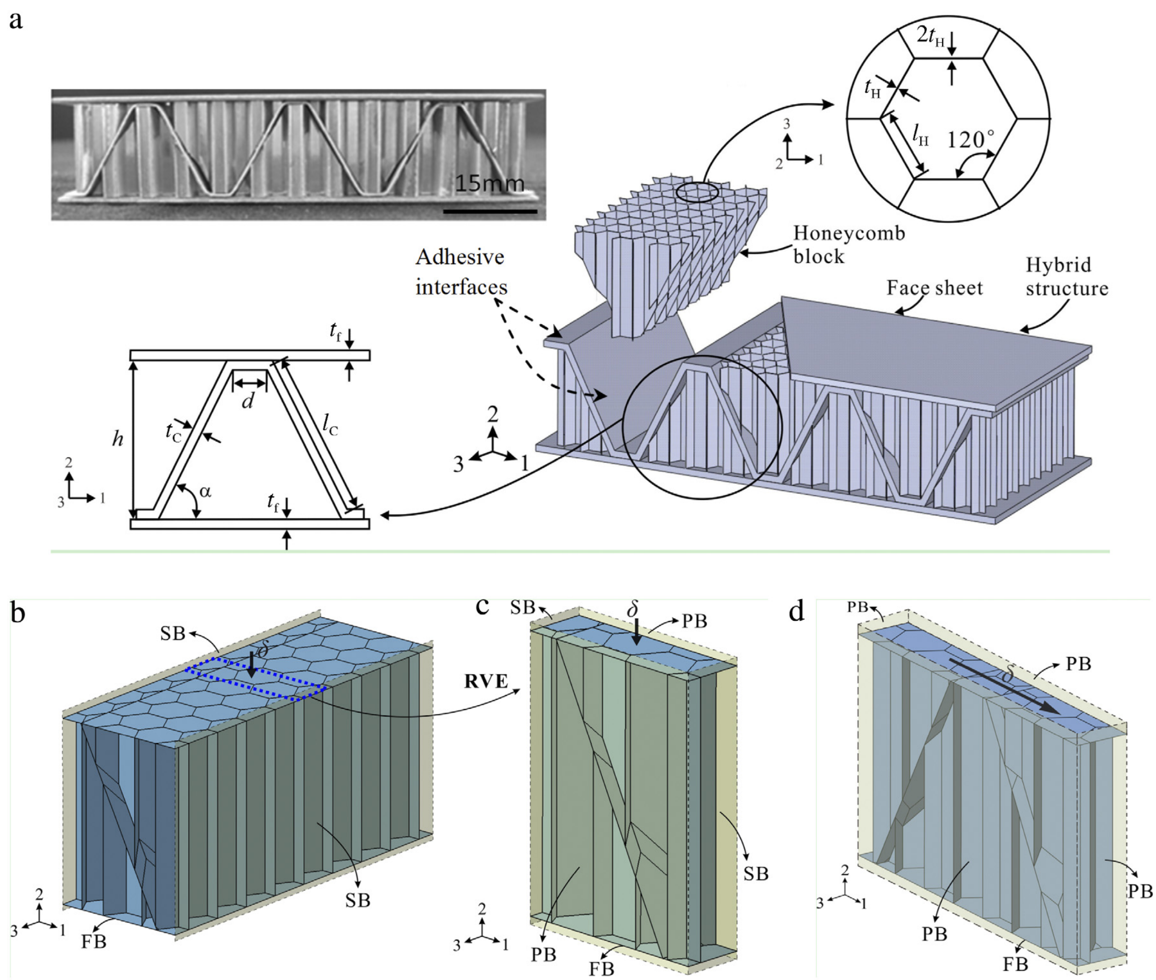

Fig. 1. (a) Schematic of honeycomb–corrugation hybrid sandwich; (b) half unit cell; (c) representative volume element (RVE) model for out-of-plane compression; and (d) RVE model for transverse shear. SB: symmetric boundary. PB: periodic boundary. FB: fixed boundary.

attractive for energy absorption applications because large forces are transferred while limited amount of energy is absorbed [7].

Recently, to increase further the specific strength and specific absorbed energy (SAE) of either honeycombs or corrugations, the concept of foam filling to construct hybrid-cellular materials has been exploited. The performance benefits of foam filling to sandwiches having honeycomb or corrugated cores derive mainly from the stabilizing effects of foam insertion on the buckling of constituent members (e.g., cell walls). For sandwich plates with foam-filled Al honeycomb cores subjected to uniform out-of-plane compression [8–10], foam filling increases both the mean crushing strength and energy absorption capability due to increased number and regularity of folds of honeycomb cell walls. Similarly, in the case of corrugated cores [11–14], foam filling stabilizes buckling and post-buckling of core webs, leading to synergistic benefits in strength and energy absorption.

Inspired by the beneficial effect of foam filling, this study proposes to combine honeycombs and corrugations to construct a hybrid sandwich core as shown in Fig. 1(a). The performance of the honeycomb–corrugation hybrid sandwich is investigated under out-of-plane compression, transverse shear and three-point bending, both experimentally and numerically.

As shown in Fig. 1(a), the honeycomb–corrugation hybrid core is composed of folded plates (corrugations) and trapezoidal honeycomb blocks, which is manufactured by filling the interstices of Al corrugations with precision-cut Al honeycomb blocks, bonded together using epoxy glue. Folded plates made of Al-3003-H24 and honeycomb blocks made of Al-3003-H18 are employed. The geometric parameters of the hybrid-cored sandwich specimens are: honeycomb cell length $l_H = 2$ mm, single wall thickness $t_H = 0.05$ mm, corrugated plate length $l_C = 17$ mm, corrugation angle $\alpha = 63.5°$, width of corrugation platform $d = 4$ mm, core height $h = 15.3$ mm, corrugated plate thickness $t_C = 0.2$ mm, and faceplate thickness $t_f = 1.1$ mm. Thus, the relative density $\bar{\rho}$ of the hybrid core is

$$\bar{\rho} = \bar{\rho}_C + \bar{\rho}_H(1 - \bar{\rho}_C), \quad (1)$$

where $\bar{\rho}_H$ and $\bar{\rho}_C$ denote the relative density of honeycomb and empty corrugation, respectively, given by

$$\bar{\rho}_H = \frac{8t_H}{3(\sqrt{3}l_H + 2t_H)} \cong \frac{8}{3\sqrt{3}}\frac{t_H}{l_H}, \quad (2)$$

$$\bar{\rho}_C = \frac{t_C(d + l_C)}{(d + l_C\cos\alpha)(t_C + l_C\sin\alpha)}. \quad (3)$$

Firstly, quasi-static out-of-plane compression tests are performed for sandwich specimens having empty corrugated core, honeycomb core and hybrid core. The measured compressive stress versus strain curves are presented in Fig. 2(a). The flow stress of the hybrid-cored sandwich is seen to be significantly higher than that obtained from summing the constituent contributions, i.e., curve 'Sum' in Fig. 2(a). The interaction effect between the curves of 'Honeycomb–corrugation hybrid' and 'Sum', represented by the shaded area in Fig. 2(a), is strong. This implies that the compressive stiffness, strength and energy absorption of both constituents (i.e., honeycomb and corrugation) are