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Foam filling radically enhances transverse shear response of corrugated sandwich plates

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ABSTRACT

To improve the poor transverse shear resistance of corrugated sandwich cores, the present study uses a combined analytical and numerical approach to exploit the idea of filling core interstices with polymer foam. For foam-filled corrugated cores under transverse shear, four collapse modes are considered: elastic buckling, plastic buckling or yielding/fracture of corrugated strut, interfacial debonding/sealing off between corrugation platform and face sheets, and foam shear failure. Analytical models are constructed to determine the transverse shear stiffness and strength. To estimate the elastic/plastic buckling strength of a corrugated strut, the foam insertions are treated as a superposition of Winkler type elastic foundations to support the strut against buckling. Finite element simulations are carried out to validate the model predictions, with good agreement achieved. The sensitivity of transverse shear strength and failure mode to corrugation angle, strut slenderness and strain hardening of strut parent material is systematically studied; collapse mechanism map is constructed, and minimum weight design is carried out. Whether the sandwich is made of metal or fiber-reinforced composite, it is demonstrated that the foam-filled corrugated core exhibits radically enhanced transverse shear response, outperforming competing core topologies such as hollow pyramidal lattices and square honeycombs on the basis of equal mass.

1. Introduction

Lightweight sandwich constructions have gained structural preponderance over monolithic materials due to superior specific stiffness/strength and potential for multifunctional applications. The face sheets of a sandwich structure are typically made of metal or laminate composite, while the core is consisted of stochastic foam or periodic lattice structure such as truss and honeycomb. In recent years, there is also a growing interest in exploiting the stochastic foam as a filling material to enhance, simultaneously, the load-bearing and energy absorption capabilities of traditional lightweight structures, such as hollow tubes and sandwich constructions having flow-through, periodic lattice cores [1–6]. At present, existing studies on these foam-filled sandwiches have focused mainly on out-of-plane compression and three-point bending responses, both quasi-static and dynamic, which is important for understanding their blast resistance and indentation performance. However, shear response is of equal significance, as bending of the sandwich gives rise to transverse shear loading and to the possibility of collapse of the core in shear. Usually, core collapse in shear dominates the failure of sandwich beams and plates with thick cores and relatively thin face sheets.

Existing literature on the shear responses of various periodic lattice structures [7–12] demonstrated that while hollow/solid pyramidal lattices and honeycombs outperform corrugation lattices in transverse shear (loading direction aligned perpendicular to the prismatic direction), corrugations in longitudinal shear (loading direction aligned with the prismatic direction) may be comparable with pyramidal lattices and honeycombs. However, although corrugations may not be the best lattice topology in terms of mechanical stiffness/strength [10], corrugate-cored sandwich constructions have enjoyed widespread applications in areas of packaging, building and transportation industry (e.g., skin frame of high-speed trains and rocket engine shells), which is attributed mainly to their relatively low manufacturing costs. Under longitudinal shear, a corrugated sandwich core usually collapse with plastic shear wrinkling in cell walls [10], analogous to shear of honeycombs [11]; in comparison, under transverse shear, the

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strength of the corrugated core is governed by Euler elastic/plastic buckling of the compressed constituent struts, similar in magnitude to that found under out-of-plane compression. Hence, the shear response of a corrugated core exhibits great anisotropy, poor in transverse shear and excellent in longitudinal shear.

As a kind of hybrid cellular structure, metallic corrugation filled with closed-cell metal foam has been investigated, both experimentally and numerically [6,13,14]. It is demonstrated that, when used as sandwich core, it exhibits superiority in both strength and energy absorption under quasi-static out-of-plane compression and transverse three-point bending over the traditional empty corrugated core. In addition, using finite element (FE) simulations, Vaziri et al. [1] assessed the effect of polymer foam filling on the mechanical properties of corrugated metallic sandwich plates. Foam-filled corrugated cores in longitudinal shear were found to have greater shear strength than equivalent unfilled ones, as foam filling effectively stabilized the corrugated struts against buckling. Nevertheless, thus far, no study focuses specifically on the transverse shear behavior of foam-filled corrugated cores. This deficiency will be addressed in the present study. We expect that inserting foams into the interstices of a corrugation may significantly enhance its transverse shear properties on the basis of equal mass.

This study is mainly focused upon how to accurately predict the equivalent transverse shear modulus and strength of polymer foam-filled corrugated sandwich cores in terms of corrugation topology and properties of constituent materials. In Section 2, upon specifying the problem, analytical models are developed for equivalent transverse shear modulus and strength that are dominated by four failure modes: *elastic buckling, plastic buckling* or *yielding/fracture* of corrugated struts, *interfacial debonding/sealing off* between corrugation platform and face sheets, and *foam shear failure*. To validate the prediction accuracy of the developed analytical models, FE models for foam-filled corrugated cores are constructed in Section 3. In Section 4, the influence of key geometrical parameters and strain hardening of strut parent material upon the transverse shear strength is discussed, and a collapse mechanism map is constructed. Consequently, minimum weight designs of the foam-filled corrugated core under transverse shear are given. Finally, the influence of strut parent material on minimum weight design is investigated, and the transverse shear strength of the foam-filled corrugated core is compared with competing topologies.

2. Analytical models

Fig. 1(a) and (b) presents schematically a foam-filled corrugated sandwich plate and the corresponding unit cell (foam insertion excluded for clarity), respectively. The sandwich structure is characterized by inclination angle θ, core web thickness t, length l, platform width f, core height $H = l\sin\theta + t$, and foam density ρ_f. Let the relative density $\bar{\rho}$ be defined as the ratio of the average density ρ_c of foam-filled corrugated core to the density ρ_s of corrugation material, as:

$$\bar{\rho} \equiv \rho_c/\rho_s = \lambda + (1-\lambda)\rho_f/\rho_s \tag{1}$$

where λ denotes the volume fraction of corrugation occupied by folded plates, given by [15]:

$$\lambda = \frac{(l+f)t}{(f + l\cos\theta)(t + l\sin\theta)} \tag{2}$$

Eq. (1) ignores the addition to mass by welding flux or adhesive glue, which is considered small relative to the mass of corrugation. Upon introducing two dimensionless parameters: $\alpha \equiv f/l$ and $\beta \equiv t/l$, λ can be rewritten as:

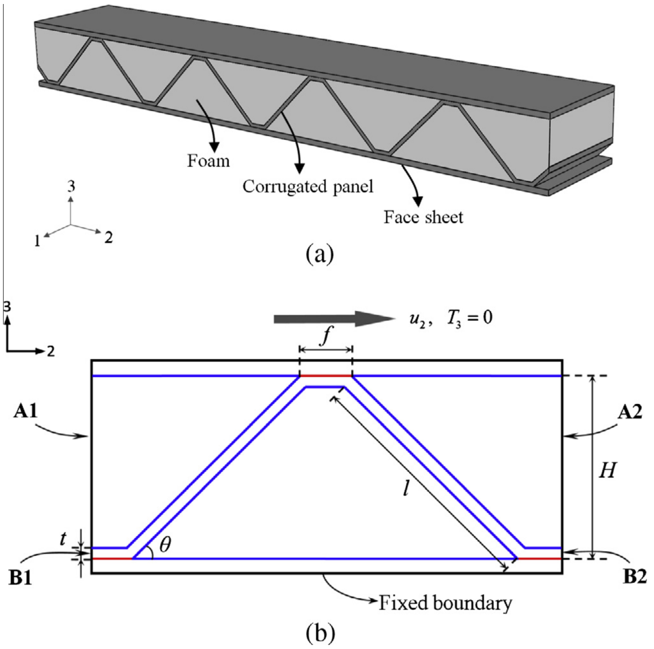

Fig. 1. Schematic of (a) foam-filled corrugated sandwich plate and (b) unit cell with additional details for finite element simulation: loading method, periodic boundary conditions, and interface condition. Red lines denote penalty contact and finite tangential sliding with the shear stress limit for failure prescribed as τ_b. Blue lines denote perfect bonding. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

$$\lambda = \frac{(1+\alpha)\beta}{(\alpha + \cos\theta)(\beta + \sin\theta)} \tag{3}$$

which, in the limit of vanishing platform volume, reduces to that obtained by Côté et al. [10]:

$$\lambda = \frac{2\beta}{\sin 2\theta} \tag{4}$$

The transverse shear response of an empty or foam-filled corrugated sandwich core may be simplified as a planar deformation problem. Thus, a corrugated panel with small t/l is taken as an inclined strut fully bonded to the face sheets which, under pure shear loading, may be treated as a rigid body, with no rotation at both ends. Hence, its ends may be treated as clamped, as confirmed by FE simulations (see later). It is further assumed that the foam and the corrugated panel are perfectly bonded at the interfaces, so that close contact with each other is maintained during deformation and there is no slipping at the interface.

To facilitate theoretical modeling, an idealized unit cell model is considered, as shown in Fig. 1(b). With planar deformation assumed, plane strain deformation prevails so that the corrugated panel has effective Young's modulus $\bar{E}_s = E_s/(1-\nu^2)$ and yield stress $\bar{\sigma}_Y = 2\sigma_Y/\sqrt{3}$. Similarly, the foam insertion has effective Young's modulus $\bar{E}_f = E_f/(1-\nu_f^2)$. Here, E_s, ν and σ_Y denote the Young's modulus, Poisson ratio and yielding stress of the core web material, while E_f, ν_f and τ_{fc} denote the Young's modulus, Poisson ratio and shear strength of the foam material, respectively.

2.1. Equivalent shear modulus

With reference to Fig. 1, the equivalent transverse shear modulus G_{23} of the foam-filled corrugated core may be obtained by superposition of the contributions from corrugation and foam [1], as: