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Damage behavior of a bonded sandwich beam with corrugated core under 3-point bending

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ABSTRACT

In this paper, the finite element method (FEM) is employed for analyzing the strength of a bonded sandwich beam with corrugated core. The adhesive layer (AL) is discretized and modeled with beam elements. A strength criterion and stiffness degeneration law of an AL is proposed. Effects of the configuration of the corrugated core on structural strength are investigated using a representative beam model containing three panels bonded with two corrugated layers. Two major geometrical parameters are considered: the angle between the oblique side and the horizontal bonding side of the corrugated layer and the overlap length of the two corrugated layers on both sides of the central panel. Numerical results obtained from 3-point bending tests show that the beam structure possesses maximum strength when the angle equals 90° and the overlap length of two corrugated layers is equal to the length of the horizontal bonding side of the corrugated layer. The crack expansion in ALs is also analyzed. It is found that the possibility crack expansion in the ALs near the upper and lower boundary is obviously greater than that in ALs near the neutral layer of beam structure. Furthermore, the flexibility of a bonded structure can be improved by enhancing the strength of the AL boundary.

1. Introduction

By combining different single phase materials appropriately, a composite can exhibit much higher physical or mechanical properties than any of its single phases [1]. This property has led to the wide application of advanced composites in engineering in the last half century. In particular, lightweight composites including sandwich panels with lattice core are popular in aeronautics, aerospace, electronics, automotive, construction, sports, and packaging [2–7].

Generally, a lightweight sandwich panel can be fabricated by bonding or welding a core with two panels. Bonded joints are expected to sustain loads for considerable periods of time. Besides the mechanical properties of solids in the panel, *two major factors* can influence the mechanical behavior of a sandwich structure. *One* is the topology or lattice configuration of the core, such as hexagonal, cross section, Kagome, triangle, diamond, and so on. For example, Evans et al. [8] compared the multifunctional performance of stochastic (foamed) cellular metals with periodic cells. Gu et al. [9] studied the heat transfer properties of cellular material with various cell morphologies and cell arrangements. Wicks and Hutchinson [10] investigated the mechanical properties of sandwich structures with truss cores. Kooistra et al. [11] investigated the compressive behavior of lattice truss structures made from aluminum alloy. Zhang et al. [12] used a numerical method to investigate the energy absorption capabilities and deformation modes of six different honeycomb sandwich circular columns under axial crushing loads. *The other* factor is the type of joining between the core and panels. Two main bonding approaches, i.e., mechanical fastening (including welding [13], riveting [14], and bolting [15]) and adhesive bonding, are popular in practical engineering applications. Compared with the mechanical fastening method, the adhesive bonding method has advantages such as absence of stress concentration, high efficiency of connection, light weight, good comprehensive mechanical properties, and low manufacturing cost. In particular, when the strength difference between the two adherends is relatively high and one of the adherends has small thickness, the adhesive bonding method might be the first choice to join the parts together [5].

In adhesive bonding composites, the strength of bonded structure is determined mainly by bonding strength, which locally depends upon the lowest strengths among adhesive, adherends, and their interfaces (see Fig. 1). Great efforts have been made to obtain a closed-form solution or numerical results of bonded joints in recent years [16]. For example, Stratford and Cadei [17] used a closed-form solution and finite difference methods to study the elastic shear and peel stresses in an adhesive joint. de Morais et al. [18] investigated the failure of adhesive joints using a fracture mechanics model. Damage analyses of adhesively bonded single lap joints in composite adherends were provided by Panigrahi [19]. Banea and Silva [20] reviewed the numerical methods

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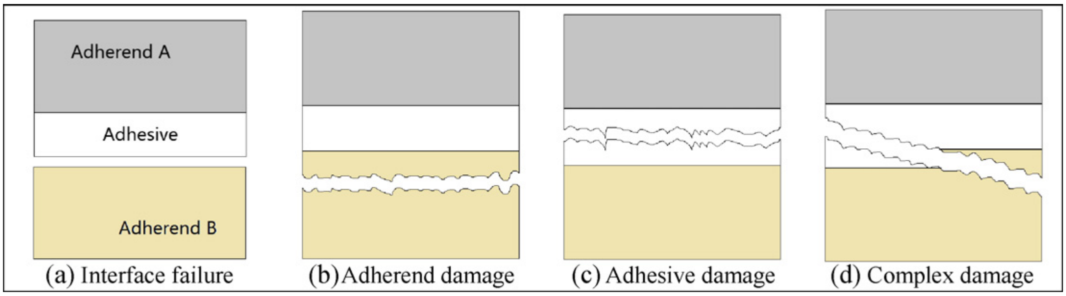

Fig. 1. Failure forms of a bonded joint.

for stress analysis to predict failure of adhesive bonding in composite materials. Silva et al. [21] presented an extensive literature review on existing analytical models for both single and double-lap joints. Huang [22] presented an analytical model of sandwich beams with adhesive layers (AL). Jen and Chang [23] implied that the major failure mode of a sandwich beam is adhesive debonding between the panels and core. Jen et al. [24] analyzed relations between the amount of adhesive and the fatigue behavior of adhesively bonded aluminum honeycomb sandwich beams. Their experimental results proved that higher amounts of adhesive lead to higher fatigue strength. Jen and Lin [25] investigated the temperature effect of adhesives on the fatigue strength of adhesively bonded sandwich beams with aluminum honeycomb core.

From the above review it is evident that most existing work has focused on either the effect of configuration of the core or the effect of bonding strength on the mechanical behavior of a composite structure. Little attention has been given to simultaneous consideration of core configuration and bonding strength of a lightweight sandwich structure. In the present study, a bonded sandwich beam with corrugated core is considered and the effects of both the shape of the core and the bonding strength of the beam are discussed. Recently, corrugated sandwich composite structures attract much attention on their bending strength and crashing behavior. For instance, Hou et al. [26] investigated the behavior of corrugated sandwich panels with the trapezoidal and triangular cores subjected to crashing load. Zhang et al. [27] presented parametric studies on the three-point-bending and compressive properties of corrugated sandwich coupons by experiments. By experiments, Yan et al. [28] tested the stiffness and strength of a sandwich beams with aluminum foam-filled corrugated cores and implied that the all-metallic sandwich structure with foam-filled corrugated cores can bear crushing/impulsive loading very well. In the present study, the damage behavior of a bonded sandwich beam with corrugated cores is studied by numerical methods. The effect of the geometry of the cores on the damage behavior is investigated. Commonly, the AL is modeled with a plate/shell element or a 3-dimensional element. In the present study, a beam element model with related strength criterion is developed for analyzing the damage of AL.

2. Methodology

2.1. Beam structure model with bonded sandwich core

A beam shown in Fig. 2 is investigated. The core of the beam is bonded together using a panel (black layer) and corrugated plates (orange part). The AL (blue layer) is placed in piecewise. In a bonded structure, the thickness of the AL (Fig. 2) is usually much less than that of the structure.

Typically, the corrugated plate is produced with a periodic unit cell. The parameters of a unit cell are defined as follows. θ is the angle between oblique part of corrugated plate and AL (see Fig. 2). l_0 is the width of the AL, b the height of the corrugated plate, w is the width of overlap between two adjacent corrugated plates (see Fig. 2), t is the thickness of the AL, and n is the total number of corrugated layers in the beam. The effects of θ and w on the strength of a beam are studied in the following sections.

2.2. Equivalent replacement of cementing layer

For simplicity and without loss of generality, the AL is replaced by (2-nodal) beam elements in the analysis. The damage process of AL is shown as the crack extension process of the beam elements. Fig. 3 shows the replacement process of the AL. The original elements in Fig. 3(a) are bonded with two three-dimensional (3D) elements for the upper layer (UL) and the lower layer (LL) and the AL. Fig. 3(b) displays the replacement of the AL with four legs. The cross sectional areas of the legs are identical, and each leg is a quarter of a beam element when the leg is within the AL. If the leg is on the boundary of the structure, the leg is only a half of the beam element. If the leg is on a corner of structure, it is a beam element whose cross sectional area is one quarter that of a cylinder beam element. Finally, the elements for the UL and LL are connected with beam elements (four quarters; it is noted that, as there are four elements adjacent each other, the four quarters are combined into one beam element with a circular cross section) as shown in Fig. 3(c).

After the replacement, the cross sectional area of the AL modeled by the beam elements is different from that modeled with the original elements. To keep the mechanical behavior of the structure equivalent, the (tension/compression or shear) stiffness of the original AL should be equal to those of the replacement.

For example, under the same load, the following equation should be satisfied

$$A_{beam} \cdot \sigma_{i,beam} = A_{glue} \cdot \sigma_{i,glue} = F \tag{1}$$

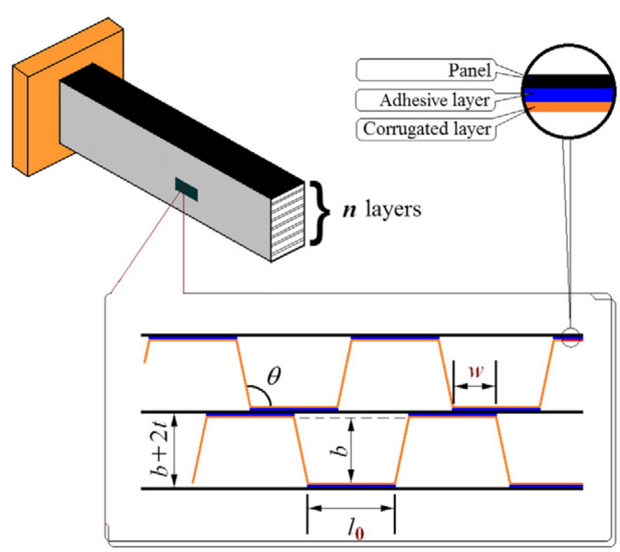

Fig. 2. A bonded sandwich beam structure with corrugated core.