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The effect of node bond adhesive fillet on uniaxial in-plane responses of hexagonal honeycomb core

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ABSTRACT

In the present work, experimental and numerical studies were conducted on the in-plane uniaxial behavior of a fiberglass/phenolic honeycomb core to investigate the effects of the node bond adhesive fillet. A non-linear finite element model (FEM) with large displacements of the repetitive unit cell of the hexagonal cell honeycomb core is employed to study the in-plane behavior numerically. The model was used to conduct a parametric study on the effects of the adhesive fillet and its geometry. To validate the numerical model, a series of in-plane quasi-static tensile and compressive tests was carried out. Numerical analysis showed that increased node bond adhesive fillet size significantly induces higher tangent stiffness of the honeycomb core. Good agreement was observed between the model predictions and test results. Analytical models from the literature without adhesive or adhesive fillet were also used for comparison.

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1. Introduction

Honeycomb cores as the main part of sandwich panels are very common in a variety of applications, including aircraft and space structures and other weight-sensitive applications. High stiffness-to-weight ratio and excellent fatigue resistance lead to the wide use of sandwich panels in aerospace products [1,2]. Honeycomb cores are mainly made by expansion and corrugation methods [3]. In both processes, the adhesive node lines are printed on the sheet material, and then two different techniques are used to convert the sheet material into honeycomb. The node adhesive is much thicker in the corrugation process than in the expansion process. In fact, the node adhesive in corrugated cores can be 10% of the total honeycomb weight, while it is only about 1% or less in the expanded core [1]. Honeycomb cores for use in sandwich structures with curvatures are typically produced in flat sheets and then formed into desired shapes using heat.

During the analysis of large-scale honeycomb core sandwich structures, it is more efficient computationally to model the core as a continuum with equivalent mechanical properties rather than considering the detailed cellular structure. Here it should be noted that due to their inherent cellular structure, hexagonal honeycomb cores are treated as orthotropic materials, with the principal material directions defined by the ribbon (L), in-plane transverse (W), and through-thickness (T) directions, as illustrated in Fig. 1. As shown here, the cell walls parallel to the ribbon direction are thicker (double wall) owing to the bonding of adjacent ribbons.

The effective orthotropic properties of honeycomb cores can be measured experimentally or predicted using analytical and/or numerical models. The homogenization of the honeycomb core and determining the effective mechanical properties have been investigated by several researchers, and reviews of previous studies have also been documented [4,5].

Honeycomb core properties with double cell wall thickness along the ribbon direction (as a result of the expansion or corrugation manufacturing process), have been a topic of interest among several studies. Gibson and Ashby [6] developed the earliest models, which were based on the assumption that the honeycomb in-plane deformations are dominated by the bending of the inclined cell walls. In fact, the deformations of the single cell walls in their own planes and the flexure of the double walls were considered to be negligible. Masters and Evans [7] derived analytical equations for the effective in-plane elastic properties of honeycomb cores considering axial, bending, and shear deformations as well as hinging. Becker [8] derived a closed-form description for the effective core stiffness, including thickness effects based on energetic approaches. Balawi and Abot [9,10] developed a refined model that includes the cell wall radii at the intersections. Recently, Malek and Gibson [11] introduced an analytical approach for the effective elastic properties of honeycombs by modifying the analysis of Gibson and Ashby [6] to account for nodes at the intersection of the

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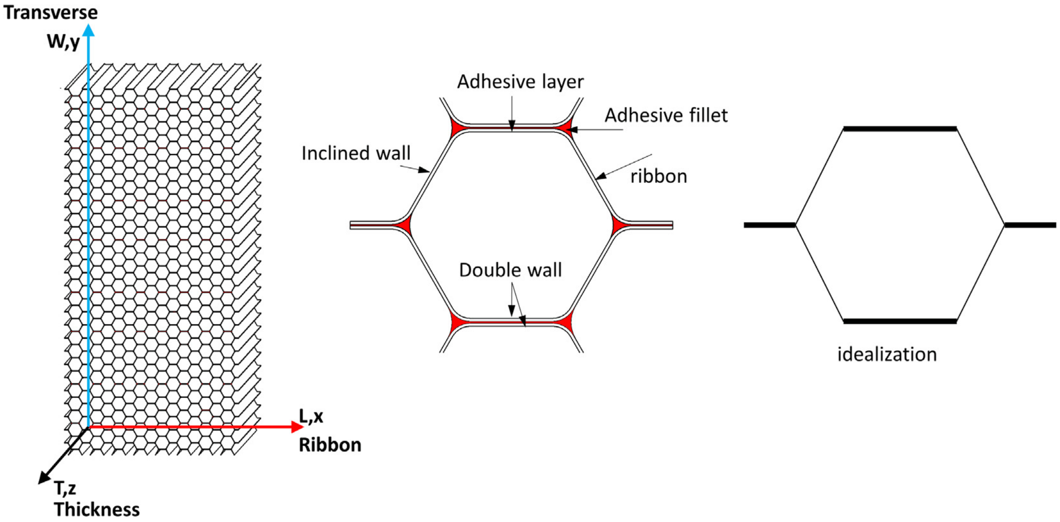

Fig. 1. Directions and details of honeycomb core material cell along with its idealization.

vertical and inclined members, and Catapano and Montemurro [12] conducted a three-dimensional (3D) numerical study to predict all elastic constants for generally orthotropic honeycombs with double-thickness cell walls using the finite element method with solid elements and to compare them with available analytical data.

Among the models developed to predict the mechanical properties of honeycomb cores, almost all of them are only applicable to ideal cores. In other words, perfect bonding is assumed between ribbons, and a detailed geometric treatment of the fillet region, as shown in Fig. 1, is ignored in the analyses [13]. Moreover, most of the analytical solutions are limited to small deformations and are only applicable to honeycomb cores made of homogeneous isotropic materials. The predictions of these models are suitable for applications where the core's in-plane deformations are restricted to a small strain regime. In sandwich structures that employ high-modulus facesheets, the core deformations are constrained by the facesheets, thus facilitating the use of homogenized core properties based on a small strain assumption. However, these properties may not be suitable for applications involving large deformations such as those occurring during thermoforming of honeycomb cores to be used in curved sandwich structures. The fillets between the core cell walls and facesheets, and between the cell walls themselves, have been shown to affect the global responses of sandwich structures[13,14]. Shi et al. [14] have shown that the properties of adhesive fillets at the core and facesheet interface in a sandwich panel significantly alters their energy absorption characteristics. While Liu et al. [13] investigated the disbonding of ribbons under through-thickness compression loading of Nomex honeycomb cores, the effects of fillets between the cell wall ribbon flanks on the in-plane properties of the core has not received much attention.

In the present study, the in-plane behavior, including non-linear stress-strain responses, Poisson effects, internal force, and moment resultants in cell walls, of a fiberglass/phenolic honeycomb core were investigated experimentally and using numerical models. Unlike previous studies, this study employed a 3D representative unit cell model in which the cell walls, node bond adhesive layer, and adhesive fillets at the intersections of cell walls were modelled based on the measured geometry of a commercial fiberglass honeycomb core that was made using a corrugation manufacturing process. The main objective of this work is to evaluate the effects of node bond fillets on the homogenized stress-strain behavior of the core, which could have significant impact on the next level of structural analyses. A non-linear finite element analysis (FEA) was conducted on the honeycomb core unit cell using an MSC Marc finite element program [15] to extract the homogenized stress–strain behavior under uniaxial tension and compressive loading along the in-plane principal material directions. The analyses indicate that the in-plane behavior is, in general, non-linear in nature and dependent on the direction of loading. The tangent moduli approached the predictions of the widely used linearized models [6,7,10] for small deformations, specifically for the case without adhesive fillets. The presence of fillets was observed to increase the tangent moduli significantly and introduced anisotropy in the in-plane responses. Details of the experimental work, numerical simulations, and key observations relative to the underlying mechanisms are discussed in this paper.

2. Characterization of honeycomb core cell geometry and material

Hexcel HRP-3/8-4.5 hexagonal cell fiberglass/phenolic honeycomb core [3] was used in the present study. The core has a nominal density of 72.1 kg/m^3, cell size of 9.53 mm, and thickness of 60.9 mm. The detailed geometry of the core cells, cell walls, and node bond fillets were characterized using image analysis. Images of several honeycomb cells were captured using a 5 megapixel digital camera equipped with a telecentric lens. An optical image of a typical honeycomb cell illustrating the double walls, adhesive fillet, and cell wall curvatures at the intersections is shown in Fig. 2. The cell geometry was characterized using the dimensions summarized in Fig. 3. Images of several randomly selected cells were used to measure the cell-wall thickness, cell-wall distances,

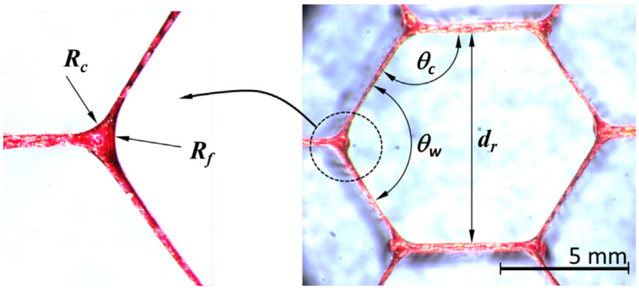

Fig. 2. Magnified image of core cell illustrating flank angle, fillet, and corner radii.