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Honeycomb sandwich residual stress deformation pattern

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ABSTRACT

Our work addresses the phenomenon of face-sheet undulation of multi-material sandwich structures with honeycomb cores. We show that the periodic deflection pattern can be caused by residual stresses and perform a parametric study to expose the sensitivity of it to geometric parameters. We also explore the effect of the deviation of the core geometry from the ideal of a regular hexagon.

1. Introduction

Sandwich plates and shells can offer very high stiffness, particularly in bending, at low weight. They are frequently found in lightweight designs produced by the aerospace and transportation industries. As the photograph in Fig. 1 exemplifies, a sandwich consists of two face sheets separated from each other by a core. Our work focuses on the interplay between face sheets and honeycomb cores manufactured by the expansion process. The name honeycomb derives from the circumstance that the core structure consists of a periodic pattern of hexagonal cells; resembling the wax cells built by honey bees in their nests to contain their larvae and stores of honey and pollen. There are a variety of materials used for the face sheets and the core. The faces are often made from lightweight materials such as aluminum or composite laminates. Honeycomb core may consist of aluminum or paper reinforced with Aramid fibers (Nomex). It is more the rule than the exception that face sheets and core consist of different materials and the combination given in Fig. 1 is typical.

Unit-cell models play a central role in the research on sandwich structural behavior [1–33]. Describing sandwich behavior at a large scale succeeds with moderate computational effort if the sandwich and its constituents are modeled with a substitute homogeneous material, or effective elastic moduli and expansion coefficients [1–4,6,7,9–11,13,15,18,20–23,27,33], where Qiao and Xu describe a multi-pass homogenization technique [10,18]. Relatively simple beam models for finding lower and upper limits for effective properties of the core material itself have been derived by [21]. More sophisticated analytical models include the effect of core thickness and face-sheet properties on the resulting sandwich properties [1,2,5,8,10,15,17]. The work of Kabashima and Ozaki [3] addresses thermal deformations and temperature expansion coefficients of sandwich structures occurring in satellites. It is noted that their unit-cell model comprises not only the core walls but also the face sheets, and because of their thinness, even the glue layer connecting them with the core. The application range of sandwich designs includes, among many others, space applications, aeronautics, and bridges [9,23,32]. Unit-cell models have also been used successfully for modeling of buckling phenomena [25], crush [14,19,24,30], or stress calculation [5,8,12,17,25,26, 30]. Among the several articles treating nonlinear problems [11,13,14,19,24,25,31] the one by Hohe and Becker [11] gives a review and cites 146 references. Unit-cell models allow deriving of simplified exact solutions but have also been used for numerical analyses with FEM [1,3,6,9,10,13,15,17,19–22,25,30,33]. Kabashima and Ozaki [3] measured and simulated coefficients of in-plane averaged thermal expansion. The effective response of the sandwich to piezo-electric induced straining of the core walls has been studied by Kalamkarov et al. [27–29]. Both groups did not consider the face-sheet undulation effect. The influence of cell geometry has been studied by several authors [7,15,19,20,25] most of whom sought to find optimum geometry for the respective considered sandwich properties. Fan et al. [25] studied the out-of-plane properties of thermoplastic hexagonal honeycombs by using finite-element analysis and took into account the fact that vertical walls of the honeycombs were not perfectly straight. We have not found other work touching the presently considered topics, namely the face-sheet undulation effect and the systematic deviation of real honeycomb core geometry from a perfect hexagon.

1.1. Topic of present work

In sandwich plates, where the core is made from a different material than the face sheets, changes of temperature or moisture

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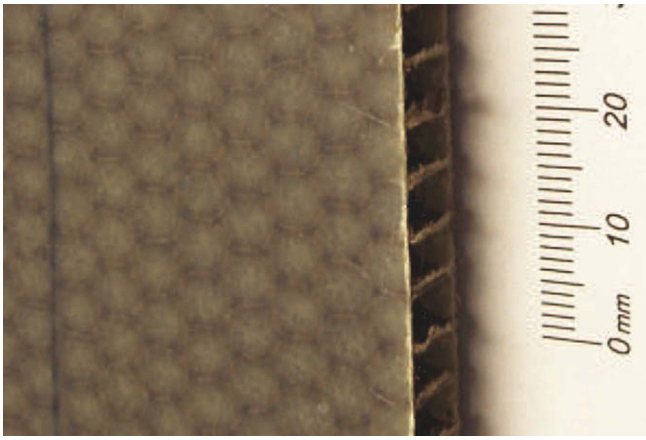

Fig. 1. Honeycomb-panel as used in airplane design: Nomexpaper–honeycomb between glass–fiber reinforced epoxy resin (source: Wikipedia).

will create residual stresses and deformations. The deformation pattern includes face-sheet undulation. The present work studies the mechanisms driving the deformation patterns and the sensitivities of these to geometric parameters. Such parameters include ratios of cell height, wall thickness or face-sheet thickness to cell size, see Fig. 2 for conventions. There the core reference directions *L*, *W*, and *T* are introduced. We will in the following use the terms *L* walls, which are called node in the figure, and *W* walls, which run diagonally and connect the nodes. Note that Fig. 2 idealizes real cell geometry, shown in Fig. 3, by portraying it as a regular hexagon. We will include the deviation of the real cell geometry from a regular hexagon in the set of parameters influencing face-sheet undulation. A typical realistic cell geometry is marked by warping of the *W*-walls due to the expansion process of honeycomb manufacture (see Fig. 4). A simple nonlinear beam model finds *W*-wall shapes which are transferred to the geometry of the unit-cell. Similar to

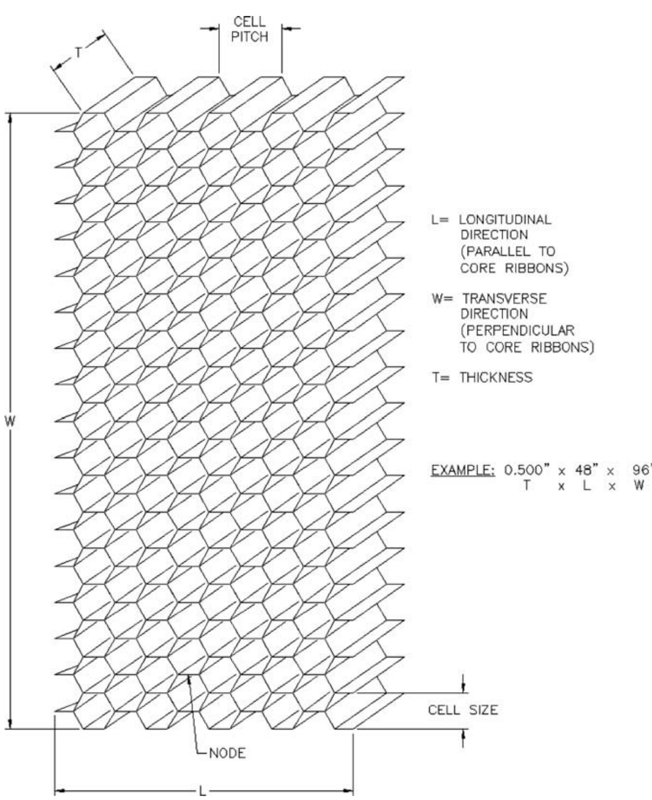

Fig. 2. Technical honeycomb terminology (source: Plascore).

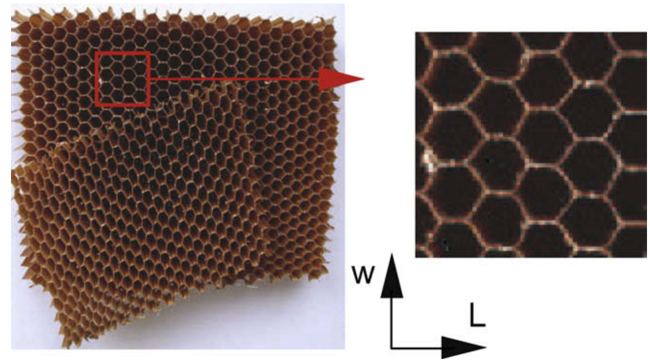

Fig. 3. Real core cell geometry.

existing previous work, it includes the core walls as well as the face sheet and takes advantage of existing symmetries; essential boundary conditions and constraining equations ensure that the unit-cell model reflects the periodicity of both the structure and the deformation pattern. We do not derive analytical solutions but point out the here considered effects by using structural analyses with the finite-element method (FEM).

2. Modelling

2.1. Honeycomb core material

The photograph of a typical Nomex honeycomb core, shown in Fig. 3, indicates that in reality no two cells are exactly alike and it catches the eye that most *W* walls appear *S* shaped instead of straight. The questions arising from the observation that there is variation in the geometry of the cells we will not address. Rather, we will present a nonlinear model for finding a typical *S* shape of a *W* wall and study its influence on the deformation patterns due to constrained material expansion.

2.1.1. Typical W wall shape

We propose that the observed *W* wall curvature results from the transforming of the honeycomb before expansion (HoBE) into the expanded sheet, shown in Fig. 4. Thereby the *L* walls, or nodes, which consist of two bonded sheets of the base material, must remain plane for symmetry reasons. However, the *W* walls are strongly bent out of their original plane so that the corrugated shape of one sheet of base material appears. If the material response during the expansion process were fully elastic, the expanded sheet would collapse back to the HoBE after the expansion step. Therefore, irreversible deformation must occur within the *W* walls in regions adjacent to the *L* walls, where the internal bending moment is highest. The remaining core wall curvature depends on the stress level at which the irreversible deformation occurs.

To obtain an estimate of the remaining *S* shapes, we use a simplified approach: instead of explicitly mapping the irreversible nonlinear material deformation process, we just assume a remaining angle $\hat{\beta}$ resulting from it. Fig. 5 illustrates that the structural model simulates one half of a *W* wall with a beam. The point at the origin of the co-ordinates coincides with the center of the *W* wall and is simply supported. The other point connects to the *L* wall and is constrained to move along the beam axis of the undeformed configuration. Deformation is caused by a prescribed rotation $\beta_z = \hat{\beta}$. A fully elastic behavior of the HoBE corresponds with $\hat{\beta} = 60^{\circ}$. If the irreversible deformation occurred at infinitely small values of stress, the beam would remain straight, or $\hat{\beta} = 0^{\circ}$. Consequently, all realistic *W* wall shapes must be estimated by enforcing rotations within the range $0^{\circ} < \hat{\beta} < 60^{\circ}$. A dedicated nonlinear