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On the buckling and crushing of expanded honeycomb

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ABSTRACT

Commonly used hexagonal honeycomb is manufactured by cold expansion of a laminate of thin metal foils that are bonded along periodically placed strips. The process results in nearly hexagonal cells with double walls in one direction, small rounding at the bent corners, and leaves behind residual stresses. This paper evaluates the effect of the expansion on the compressive response of the honeycomb. A finite element model of a characteristic cell is developed using shell elements and by applying to it the appropriate periodicity conditions. The model is first expanded mechanically producing the realistic geometry and changes to the mechanical properties of the material. The cell is subsequently compressed laterally leading first to buckling, followed by collapse by progressive folding, all similar to the behavior of ideal, stress free hexagonal honeycomb. The calculated buckling stress is about 10% higher than the ideal case, the collapse stress about 5% lower and the average crushing stress somewhat higher. In addition, the buckling and collapse stresses show some sensitivity to the size of periodic domain analyzed, as indeed was the case for the ideal case.

1. Introduction

Metallic hexagonal honeycomb remains the most commonly used core in high performance sandwich construction because of its favorable lateral specific stiffness, strength and energy absorption capacity [4]. The role of the core is to shear connect the faceplates, giving the sandwich the required bending rigidity. Thus, the anisotropic nature of honeycomb is an advantage in such applications. Most commonly used metallic hexagonal honeycomb is manufactured by mechanically expanding laminated thin metal foils, which are first bonded along periodically placed strips as shown schematically in Fig. 1 [8,11]. The process produces nearly hexagonal cells with double walls in one direction, the cause of in-plane anisotropy. The relative ease of manufacture has helped in the proliferation of this type of honeycomb.

The extensive use of expanded honeycomb in sandwich construction generated an extensive literature on the subject starting with the anisotropic elastic properties (e.g., [10,19,11,7,26,4]). The second motivation comes from the use of such honeycombs for energy absorption in a variety of quasi-static and dynamic applications (e.g., [12–16,22,21,5,1,25,27,2,24]). With few exceptions in these studies the honeycomb was assumed to be perfectly hexagonal, stress free and was assigned the mechanical properties of the original aluminum foil.

In our previous contribution to the subject of compressive properties this trend of idealized perfect hexagons was adopted also but the in-plane anisotropy was considered (Wilbert et al., 2011 hitherto referred to as [24]). Numerical models developed exploit the periodicity of the honeycomb to simulate the complete compressive response using either a single or a cluster of characteristic cells. It was demonstrated that typical thickness Al-alloy honeycombs compressed laterally first buckle elastically and subsequently collapse because of inelastic action. The buckling stress is not imperfection sensitive whereas the collapse stress exhibits some sensitivity to typical imperfections. The same models were shown to reproduce with reasonable accuracy the complete crushing response associated with progressive folding of the cell walls.

As mentioned above, the expansion process introduces changes to the inelastic mechanical properties of the foil, leaves behind residual stresses, and some rounding of the bent corners as demonstrated in the photograph of a typical node shown in Fig. 2a. The aim of the present study is to assess the effects of this manufacturing process on the calculated compressive properties. To this end, the expansion process of the Al-alloy honeycomb tested and analyzed in [24] is reproduced numerically. The model is then compressed laterally, critical buckling and collapse stresses are evaluated and compared to corresponding results from perfectly hexagonal and stress free models. The expanded model is subsequently crushed quasi-statically in order to assess the effect of the expansion process on the crushing response and energy absorption capacity.

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2. Analysis

The aim of the analysis is to first simulate the mechanical expansion process through which the honeycomb is manufactured and subsequently to laterally compress and crush the model. Honeycomb expansion was previously simulated in [18] in their study of in-plane crushing of similar honeycombs. There, the emphasis was on expanding a $m \times n$ cell section of honeycomb that was large enough to minimize size effects in the subsequent in-plane crushing. The lateral thickness was not important and the sides of the cells were modeled using custom shear deformable beam elements. By contrast, in the present problem the cell walls are modeled with S4 and S4R shell elements with a rather fine mesh that is required in order to capture accurately the buckling and collapse stresses and the concertina folding that ensues during the crushing phase of the simulation. Furthermore, as in [24], the periodicity of the nearly hexagonal microstructure will be exploited in order to keep the overall size of the calculations at a level that facilitates parametric studies. The effect of this assumption will be evaluated in a separate study in which the size of the domain analyzed is varied.

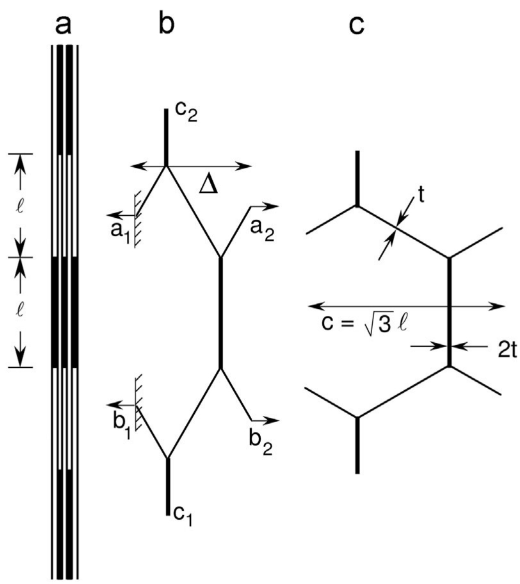

Fig. 1. (a) Laminate of periodically bonded aluminum foil strips from which hexagonal honeycomb is produced by expansion. (b) Expansion of characteristic cell and (c) its final geometry.

2.1. Expansion

The characteristic cell adopted shown in Fig. 1 is double the size of the one used in the crushing model of [24]. The model starts as a stacking of several plates of thickness t and height h that are divided into sections of length ℓ, the desired length of the cell sides, as shown in Fig. 1a. The plates are connected to their neighbors on either side via double wall thickness elements that are alternately placed along their lengths as shown schematically in the figure. For the most representative model the domain of interest (base case) has cell dimensions $\{c, h, t\} = \{0.375, 0.625, 0.00374\}$ in or {9.53,15.9, 0.095} mm. The case we refer to as the "base" model is discretized with 8316 S4 shell elements in ABAQUS Standard with 62 cells along the height. The cell height nodes along a_1 and b_1 are periodic with a_2 and b_2 while c_1 nodes are periodic with ones along c_2. All boundary nodes a_1 and b_1 in Fig. 1b are fixed in the horizontal direction, while rigid body motion is prevented by fixing nodes b_1 vertically also. Nodes a_2 and b_2 along the RHS edges are prescribed equal horizontal displacements incrementally.

As in [24], the Al-5052-H39 material is modeled as a finitely deforming J_2 solid that hardens isotropically. It is calibrated to a bilinear stress–strain response that was fitted to measured tensile tests on the honeycomb foil. It has an elastic modulus of 10^4 ksi (69 GPa), a yield stress of 36 ksi (248 MPa), a post-yield modulus of 57 ksi (394 MPa) up to a strain of 10% and is perfectly plastic at higher values (true stress–logarithmic plastic strain version).

Fig. 3 shows the calculated stress–displacement response during the expansion process ($\sigma_{ex} \equiv$ force/final cross sectional area of the cell $\approx 3\ell h$; Δ is defined in Fig. 1b and c is the desired width of the nearly hexagonal cell). The initial and five deformed configurations of the cell corresponding to the numbered points on the response are shown in Fig. 4. Initially, the response is relatively stiff but, as inelastic action sets in, a knee leading to a regime of smaller slope develops. Configurations ①–③ show the expanding cell at different stages of deformation. At higher values of Δ, membrane tension starts to develop in the rotated cell sides and the response progressively stiffens. The honeycomb is pulled beyond the required width (point ④) to allow for the elastic springback on unloading (point ⑤). Unloading is achieved by incrementally releasing the nodes along a_2 and b_2. In the case shown, point ④ is at $\Delta = 1.0455c$ and point ⑤ at $\Delta = 1.0c$ (point ④ is determined iteratively).

The main effect of the expansion on the geometry is some rounding of the walls at the corners of the cells that is illustrated by the zoomed in view of one of the nodes shown in Fig. 2b. Its similarity to the photographed corner in Fig. 2a is quite clear. It is

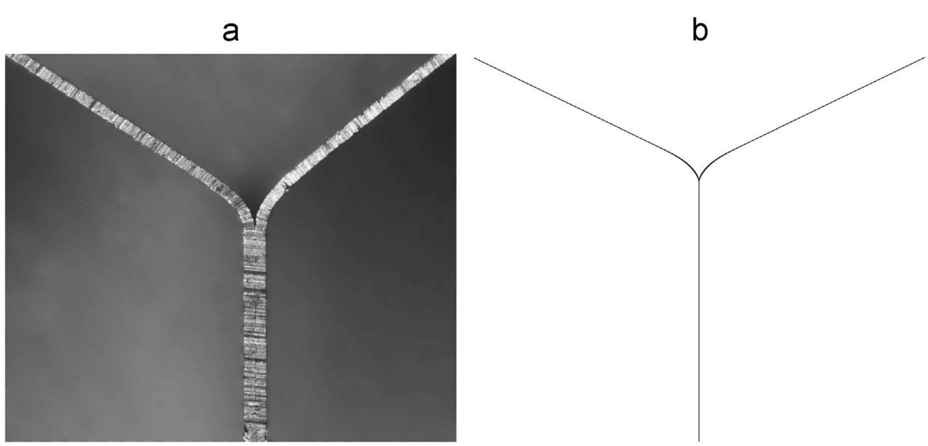

Fig. 2. Nodes of expanded honeycomb with double walls in the L-direction and single wall wings. (a) Photomicrograph of Al-5250-H39 node and (b) node of FE model of the expansion process.

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