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# Buckling and progressive crushing of laterally loaded honeycomb

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ABSTRACT

This paper presents a comprehensive study of the lateral compressive response of hexagonal honeycomb panels from the initial elastic regime to a fully crushed state. Expanded aluminum alloy honeycomb panels with a cell size of 9.53 mm, a relative density of 0.026, and a height of 15.9 mm are laterally compressed quasi statically between rigid platens under displacement control. The cells buckle elastically and collapse at a higher stress due to inelastic action. Deformation then first localizes at mid-height and the cells crush by progressive formation of folds; associated with each fold family is a stress undulation. The response densifies when the whole panel height is consumed by folds. The buckling and crushing events are simulated numerically using finite element models involving periodic domains of a single or several characteristic cells. The models idealize the microstructure as hexagonal, with double walls in one direction. The nonlinear behavior is initiated by elastic buckling while inelastic collapse that leads to the localization observed in the experiments occurs at a significantly higher load. The collapse stress is found to be mildly sensitive to various problem imperfections. The subsequent folding can be reproduced numerically using periodic domains but requires a fine mesh capable of capturing the complexity of the folds. The calculated crushing response is shown to better resemble measured ones when a $4 \times 4$ cell domain is used. However, the average crushing stress can be captured with engineering accuracy even from a single cell domain.

## 1. Introduction

Honeycomb is a two-dimensional cellular material that is relatively strong and stiff along the normal to the microstructure but compliant and weak in-plane. It is widely used as core in sandwich construction where its role is to transfer shear loads between the faceplates (Allen, 1969, Marshall, 1982). Hexagonal cells are most common but circular, square and other cell geometries including ones that are auxetic and others that can accommodate bending of a sheet exist (Hexcel, 2010). Honeycomb is made from most materials, metals, polymers, paper, etc., to fit the application. Their wide use stems from their excellent specific stiffness and weight, their outstanding energy absorption characteristics and their cost effectiveness (Gibson and Ashby, 1997).

The wide use of honeycomb in practice generated a need for establishing their mechanical properties and this spawned an extensive literature on the subject starting from the anisotropic elastic properties, the onset of “yielding” and collapse, and the crushing response (e.g., Gibson and Ashby, 1997). Of all honeycombs, metallic ones with hexagonal cells have received the most attention. The extensive literature on the out of plane mechanical behavior was motivated first by the design needs of sandwich construction (e.g., Kelsey et al., 1958; Penzien and Didriksson, 1964; Grediac, 1993; Zhang and Ashby, 1992; Gibson and Ashby, 1997). The second motivation comes from the use of such honeycombs for energy absorption in a variety of quasi-static and dynamic applications (e.g., McFarland, 1963, 1964; Wierzbicki, 1983; Wierzbicki and Abramowicz, 1983; Goldsmith and Sackman, 1992; Mohr and Doyoyo, 2003, 2004a,b; Aktay et al., 2008; Yamashita and Gotoh, 2005; Zhao and Gary, 1998; Chen et al., 2009).

A similarly large literature on the in-plane properties is mainly motivated by the similarities between the behavior of three-dimensional cellular materials, namely foams, and that of honeycombs loaded and crushed in-plane; in other words, here the honeycomb represents a two-dimensional model for the more complex foams with space-filling three-dimensional microstructures (e.g., Gibson et al., 1982; Klintworth and Stronge, 1988; Papka and Kyriakides, 1994, 1998; Triantafyllidis and Schraad, 1998).

The present study is concerned with the more traditional problem of transverse compression. In particular, we aim to establish all aspects of the compressive response of honeycomb sandwich panels; that is, the initial linearly elastic behavior, the onset of instability, the onset of collapse, its localization, and the progressive folding and crushing under persistent compression. Of these properties, the crushing behavior, or in other words the energy

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