Composite Structures 94 (2012) 2296–2305

Contents lists available at SciVerse ScienceDirect

Composite Structures

journal homepage: www.elsevier.com/locate/compstruct

# Functional grading in hierarchical honeycombs: Density specific elastic performance

C.M. Taylor, C.W. Smith *, W. Miller, K.E. Evans

College of Engineering, Mathematics and Physical Sciences, University of Exeter, Exeter, UK

ARTICLE INFO

Article history:
Available online 30 January 2012

Keywords:
Functionally graded
Hierarchy
Honeycombs
FEA

ABSTRACT

The introduction of hierarchy into structures has been credited with improving their elastic and other properties. Similarly, functional grading has been demonstrated to increase the damage tolerance of honeycomb structures, although with the penalty of reduced Young's modulus or increased density. The combination of both hierarchy and functional grading has not been reported for honeycomb structures, although it is known in natural materials. A parametric numerical modelling study has been made of the in-plane elastic properties of honeycombs and how they are affected by functional grading and hierarchy, and importantly to establish whether it is possible to avoid reductions in Young's modulus. A set of analytical models has been developed to describe functional grading and hierarchy in honeycombs, based upon beam mechanics and the transform section method. The conditions for transition of a hierarchical honeycomb in behaviour from that of a discrete structure to that of a continuum are established. Furthermore, conditions are established for which hierarchical honeycombs, uniform or functionally graded, can surpass in-plane Young's moduli of conventional honeycombs a by factor of up to 2, on an equal density basis.

© 2012 Elsevier Ltd. All rights reserved.

## 1. Introduction

The excellent density specific mechanical properties of honeycombs make them desirable as light weight structures and particularly as cores in sandwich panels. Honeycombs are widely used in industries where these properties are in demand, e.g. aerospace [5,14]. Reducing the density of honeycombs without sacrifice to their mechanical performance is advantageous. Honeycombs are often able to retain functionality after impact due to the progressive collapse inherent with their in-plane bending dominated structure [13,27,6].

There has been lots of interest in the Functional Grading (FG) of materials such as composites in recent years [4], and whilst there are a few studies of functional grading of honeycombs, in the main this has been for thermal or electrical properties [24,29]. Mechanical properties were investigated by Ajdari et al. [2] concluding that the elastic modulus was sensitive to the density gradient across the domain. Other work on functional grading in honeycombs has focussed on impact energy absorption, Ajdari et al. [3]. Similarly, little work has been undertaken on hierarchy in honeycombs [17,16,7,26] but this has shown that improvements in elastic properties on a density specific basis are possible with careful design. The authors are not aware of any work combining functional grading and hierarchy for honeycombs in synthetic materials, although both phenomena are known to occur simultaneously in many natural materials [8,9,25]. Many of these natural materials posses excellent density specific elastic and other properties [8–10].

Materials that have a gradual change in either the volume fraction or physical properties of constituent materials within a composite are often described as being functionally graded. Functional grading of materials in general is now in a fairly mature state, with manufacturing methods for FG composites and modelling methods to predict their properties now developed [4,19,21,22]. Work focusing on the elastic properties of FG honeycombs is limited, with studies by Ajdari et al. [2], Lira and Scarpa [18], and Taylor et al. [26], demonstrating how global elastic properties of honeycombs are indeed sensitive to the various parameters associated with functional grading. There has been more work undertaken on failure, dynamic and impact properties of FG honeycombs demonstrating improved performance *vs* ungraded honeycombs [3,15,1,28]. Whilst there is good evidence for beneficial effects of FG in terms of failure and damage processes in honeycombs, little work has been done to establish if there is a penalty in elastic performance for FG, with some indications from Ajdari et al. [2] and Lira and Scarpa [18] that there are indeed such penalties in some cases.

Hierarchy has been the subject of much investigation in natural and other materials [8,9] but little effort has been given to fundamental understanding of elastic properties and hierarchy. Hierarchical structures can be given a hierarchy order number which

* Corresponding author. Tel.: +44 0 1392 263652; fax: +44 0 1392 217965.
E-mail address: c.w.smith@ex.ac.uk (C.W. Smith).

0263-8223/$ - see front matter © 2012 Elsevier Ltd. All rights reserved.
doi:10.1016/j.compstruct.2012.01.021

describes the number of distinct size scales at which there is architecture; a conventional honeycomb has an order number of one. The primary works on elastic properties and hierarchy are the work of Gibson et al. [12] and Lakes [17]. Gibson et al. [12] showed that the elastic properties of a honeycomb were not dependent upon absolute size of the cells, but rather the aspect ratio of the cell ribs. Coarser or finer honeycombs would therefore have the same properties as long as the cell rib aspect ratio was unchanged. This underlay the independence of elastic properties of honeycombs to their hierarchical order in Lakes [17]. Recently the present authors [26] have shown that hierarchy in hexagonal honeycombs usually does lead to large changes in elastic properties, because (i) for constant relative density the aspect ratio of cell ribs does change with hierarchical order numbers greater than one and (ii) mixed shear and flexure deformation modes can make some cell ribs more compliant than their aspect ratio would predict.

Kooistra et al. [16] and Fan et al. [7] have both developed case studies of hierarchical sandwich panel cores with improved performance over existing non-hierarchical (conventional) configurations. The work herein explores how in-plane mechanical properties of honeycombs are changed by functional grading of a hierarchical structure.

## 2. Methods

The in plane elastic properties of FG Hierarchical Honeycomb (HH) was calculated via numerical models which considered each unit cell as a discrete structure, and made no assumptions about sub-cells as continua and via analytical models which assumed that sub-cells could be considered as continua. In this sense the numerical models provided validation for the analytical models.

### 2.1. Finite element model

The various parameters describing honeycombs, functional grading and hierarchy are shown in Fig. 1 and defined in the following. The cells of conventional and HH honeycombs have ribs of length $l$ and $h$, and thickness $t$, as shown in Fig. 1 in both a conventional and HH. The aspect ratio of a honeycomb rib is defined as its length divided by its thickness, as shown in Eq. (1) The parameter values for super- and sub-structure cells are noted by the subscripts *sub* and *sup* (referring to sub-and super-structure parameters respectively), and as described in [26].

$$a = \frac{l}{t} \tag{1}$$

The first step in applying functional grading to the honeycombs was to determine the length scale of the sub-structure, relative to that of the super-structure, at which it could be considered to be a continuum. The ratio of the lengths in the super-and substructure is the hierarchical length ratio (HLR) $\lambda$ and is defined according to Eq. (2). The critical value of the HLR at which continuum behaviour was attained was determined by iteratively decreasing the value of $\lambda$ for three example HHs of different aspect ratios ($\alpha_{sup} = 11.5$, $\alpha_{sup} = 2.88$ and $\alpha_{sup} = 1.15$).

$$\lambda = \frac{l_{sub}}{l_{sup}} \tag{2}$$

To change $\lambda$ the lengths $l_{sub}$, $h_{sub}$ and $t_{sub}$ of the sub-structure were iteratively decreased, while lengths $l_{sup}$, $h_{sup}$ and $t_{sup}$ remained constant, effectively increasing the number of sub-cells spanning the thickness of the super-structure, as shown in Fig. 1. Once the critical value of $\lambda$, and thus the number of sub-cells spanning the super-structure, was determined, it was then possible to investigate non-uniform distributions of mass in the sub-structure.

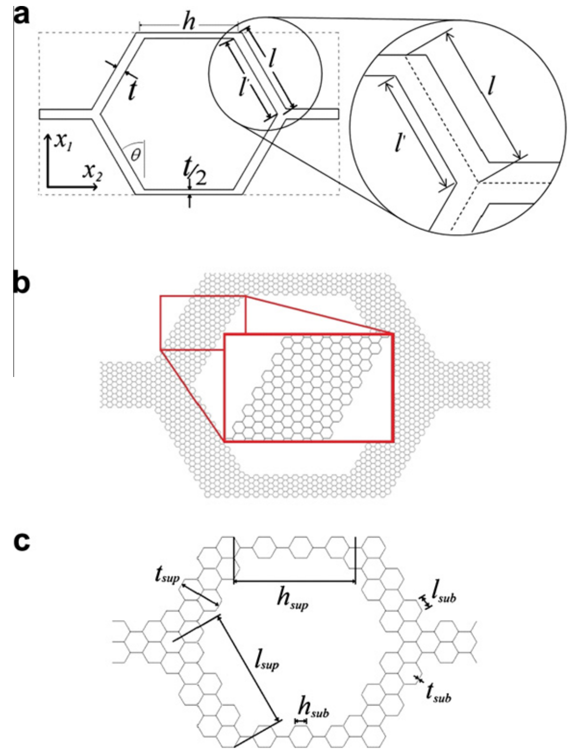


**Fig. 1.** (a) Shows the cell geometry and parameters for a conventional hexagonal honeycomb unit cell according to Gibson and Ashby's terminology. (b) A unit cell of a second order HH with a hierarchical length ratio of $\lambda = 0.015$ and a super-structure aspect ratio $\alpha_{sup} = 2.88$. (c) A unit cell of a second order HH with a hierarchical length ratio of $\lambda = 0.1$ and a super-structure aspect ratio $\alpha_{sup} = 2.88$, along with annotated terminology.

Functional grading was applied by gradually varying the thickness of sub-structure ribs $t_{sub}$ in rows of sub-cells as a function of the row's position through the thickness of the super-structure rib, see Fig. 2. There were two ways in which to implement this variation (i) by changing $t_{sub}$ and maintaining $l_{sub}$ and (ii) changing $l_{sub}$ and maintaining $t_{sub}$. A change in $t_{sub}$ was chosen since in this manner it was possible for sub-cells to tessellate but not possible if $l_{sub}$ was varied. The various distributions of $t_{sub}$ produced different distributions of mass throughout the unit cell, as shown in Fig. 2. It is important to note that the total mass of each unit cell was maintained, as was the total cell area, ensuring the exact same relative density between different distributions, by taking into account the thickness and the number of ribs for each row. Mass distributions were defined by a string of percentages of total rib thickness for four rows of sub-cells making up half a super-structure rib, see Figs. 2 and 3. Hence, a uniform distribution would be denoted as (25/25/25/25), i.e. the percentage of total rib thickness for regions 1, 2 3 and 4 are 25% each. Twelve other non-uniform distributions were also considered, listed in Table 1. These 13 distributions were considered for unit cells with a relative density of $\rho^* = 0.00577$ which is equivalent to a conventional hexagonal honeycomb when $l = h = 10$ and $t = 0.05$.

Two dimensional finite element quarter models were generated for each unique unit cell, and its in-plane axial Young's modulus calculated. A set of linear isotropic elastic constants were chosen as the constitutive material and used for all cases (specifically $E_s = 1600$ MPa, $G_s = 593$ MPa and $\upsilon_s = 0.35$). The sub and super-cells were modelled using a minimum of 20 2D Timoshenko beam elements (B21: a 2-node linear beam) per cell rib using a commercial Finite Element (FE) analysis package (ABAQUS, version 6.9. Dassault Systèmes). Boundary sharing ribs had either half thickness or half-lengths, so that the symmetry of the model allowed tessel-

Download English Version:

https://daneshyari.com/en/article/10283682

Download Persian Version:

https://daneshyari.com/article/10283682

Daneshyari.com