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Deformation mode evolutional mechanism of honeycomb structure when undergoing a shallow inclined load

Zhonggang Wang [a,b,*], Zhaijun Lu [a,b], Song Yao [a,b], Yiben Zhang [a,b], David Hui [c], Luciano Feo [d]

[a] School of Traffic & Transportation Engineering, Central South University, Changsha, China
[b] Key Laboratory of Traffic Safety on Track, Ministry of Education, Changsha, China
[c] Department of Mechanical Engineering, University of New Orleans, USA
[d] Department of Civil Engineering, University of Salerno, 84084 Fisciano (SA), Italy

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ABSTRACT

Inclined loading conditions cannot be avoided and strongly influence the mechanical response of honeycomb structures. In present study, deformation modes as well as dynamic responses of hexagonal honeycomb structures undergoing non-ideal oblique impact loadings have been investigated considering as significant parameters of the load angle (ranging from 0 to 10°) and the impact velocity (ranging from 3 to 70 m/s). Some new deformation phenomena and response modes have been observed. Evident influence of asynchronous loading as well as impact speed on the deformation mode evolution has been determined. Corresponding mode classification maps were constructed. The present study provides a significant advancement to the comprehensive understanding of the dynamic response of honeycombs, which could be used to develop more valuable guidelines for design purposes in cellular energy absorbing devices.

1. Introduction

Aluminum honeycomb structures have been widely used in kinds of industrial fields, such as high-speed train, aerospace, automobile, due to their excellent mechanical performance and high-energy absorption capacity [1,2]. In the past decades, many investigations have been carried out extensively on its stiffness, performance and mechanical behaviors by means of theoretical [3–4] and experimental [5–6] methodologies. Recently, numerical simulations have become popular, by means of which many findings have been achieved and presented in the literature (see, for instance, Wang et al. [7], Aktay et al. [8], Sun et al. [9], Papka and Kyriakides [10], Fan et al. [11], Liu et al. [12], Chen and Yan [13]). From these constructive works, the honeycomb structure has been turned out to show completely different behaviors at different loading directions. When loaded at out-of-plane impact directions, the honeycomb structure cells collapse progressively, whereas, when loaded at in-plane direction, three typical patterns of localization bands can be identified at different impact velocities, which have been summarized in Cricrì's experimental research [14], Ruan's numerical investigation [15], and Hu's work [16]. These three typical patterns of localization bands are called "X" pattern, "V" pattern and "I" pattern, respectively. At low impact velocity, localized deformation appears in the form of "X" bands ("X" mode), whereas, at high impact speed, vertical localized bands ("I" mode) are generated perpendicularly to the loading direction. A transitional "V" mode occurs at moderate impact velocities. The localized band moves toward the loaded edge for increasing values of the impact velocity.

However, such modes occur under ideal loading conditions, which never happen in the real-life situations, especially in complex engineering applications. In fact, honeycomb structures do not undergo ideal axial impacts, but oblique loading situations often happen. The investigation of the mechanical behavior of honeycomb composite structures under non-ideal loading conditions has been a popular research topic in recent years. Some significant research works were performed by Reyes et al. [17–19], Ahmad et al. [20], Zarei and Kroger [21], Greve et al. [22]. The oblique loading, an unavoidable or even common situation, represents a major threat to safety. It may cause mutation of dynamic response mode, loss of energy-absorption capacity, or even worse, it leads to an unpredictable deformation process, especially for long tandem honeycomb series as presented in Eskandarian and Marzougui's research work [23]. These phenomena, which can be collectively referred to as "oblique effects" have attracted a high attention in engineering applications. Keshavanarayana and Thotakuri [24]

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* Corresponding author at: School of Traffic & Transportation Engineering, Central South University, Changsha, China.

E-mail address: wangzhonggang@yahoo.com (Z. Wang).

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investigated off-axis compression behavior of honeycomb core with different off-axis angles. According to their investigations, the crush initiation load and crush stress decrease as the off-axis angle increasing. A more extensive study of this problem was carried out by Hong et al. [25]. In their works, detailed quasi-static and dynamic out-of-plane uniaxial crush experiments under dominant inclined loads were introduced, and empirical formulae of normalized normal crush strengths as functions of the impact velocity as well as the orientation angle were derived. All these excellent works provide a good insight into the behavior of honeycomb under oblique loading, but have a limited predictive capability for analyzing the deformation mode evolution. As a matter of fact, an effective analysis of cellular honeycomb materials subjected to compressive loadings, because of the slenderness of their longitudinal walls should include the influence of strong nonlinearities in both geometric and constitutive properties occurring at different scales. In order to account for the effects of microstructural properties of these materials on their non-linear mechanical behavior, non-linear homogenized constitutive models are widely adopted (see [26–28]). More powerful approaches able to capture the actual geometrical and/or material nonlinearities of such heterogeneous structures are the so-called multiscale approaches, grouped in semi-concurrent types (see [29–31]) and concurrent types (see [32–34]), whose accuracy is the same as the fully microscopic models, which often are not pursed in engineering practice due to the required large computational effort.

As is well known, a stable and orderly buckling process is preferable for increasing the energy absorption, especially in aluminum honeycomb. Thus, determining honeycomb's performance and mechanical behavior under oblique loading has become an urgent issue.

This paper focuses on the hexagonal aluminum honeycomb's deformation mode under oblique impact loading at different velocities ranging from 3 to 70 m/s and different inclination angles ranging from 0 to 10°. The scopes of this paper are limited to explicitly obtain the state mode evolution for honeycomb structures at oblique loading conditions and to construct complete mode classification maps. The rest of the paper is organized as follows. Section 2 establishes the detailed full-scale finite element model. In addition, it reports the model validation conducted by means of comparisons with experiments. Section 3 presents the results obtained by the parametric numerical simulations, with a special attention to the three uniaxial responses. The related mechanical properties are also derived here. Section 4 is devoted to the construction of the mode classification maps. Section 5 discusses the factors influencing the mode evolution with particular reference to angle and loading velocity. Section 6 draws some major conclusions.

2. Finite element model and experimental validation

2.1. Finite element model

All the numerical simulations have been conducted using explicit finite-element analysis program package LS-DYNA3D®. The corresponding detailed numerical models have been established, in which the cell walls of hexagonal honeycomb have been meshed with Belytschko–Tsay shell elements. Fig. 1 shows the honeycomb's geometric structure and the repeating cell. In each model of this study, the thickness t of cell wall has been set as 0.06 mm. The edge length h and the width l of the cell have been set as 4 mm. The core consists respectively of 15×15 cells for in-plane conditions (along X_1 and X_2 directions) and of 15×13 for out-of-plane conditions (along X_3 direction). The overall thickness of the specimen along X_3 direction is of 5 mm for in-plane loading conditions, and of 60 mm for out-of-plane loading conditions to capture more collapsed folds in the latter case. In order to analyze the crushing behavior along X_2 direction, for example (see Fig. 1(c)), the honeycomb specimen is placed on a fixed rigid plate and crashed by another moving rigid plate inclined by an angle θ and subjected to a constant vertical velocity v. Analogous loading conditions have been applied to study the crushing behavior along X_1 and X_3 directions. An hourglass control algorithm has been employed in the following numerical computations. The binding material between cell walls has been ignored in this paper since the adhesive has full capability to attach every cell wall. More generally, for some kinds of cellular-like materials, the debonding between cell walls within the layer of the binding material could be considered. As a matter of fact, debonding mechanisms in both static and dynamic loading conditions (see [35–37]) may lead to a premature failure of the composite structure thus compromising its energy absorption capacity. Meanwhile, this kind of debonding has not been observed in aluminum honeycomb yet, according to the existing experiments (see [4,7,15]).

The mechanical properties of cell wall material are: density $\rho = 2700\ \mathrm{kg/m^3}$, Young's modulus $E = 68.97$ GPa, Poisson's ratio $\mu = 0.35$, yield stress $\sigma_0 = 292$ MPa; moreover, the stress–strain response is idealized by a bilinear law with a post-yield modulus set as $E/100$, and its behavior is treated as rate-independent, as was done by Aktay et al. [8], Fan et al. [11], Ruan et al. [15], Hu and Yu [16], Yamashita and Gotoh [38], Liu and Zhang [39]. An automatic single surface-to-surface contact algorithm has been applied to avoid penetration between cell walls, whereas the dynamic friction factor has been set as 0.20. A convergence study with different element sizes has been carried out before the reported numerical simulations, after which the optimal element size has been deduced and set as 1 mm in each FE model.

2.2. Experimental validation

In order to assess the validity of the proposed numerical model, a uniaxial compression test is performed along the X_3 direction by employing the universal testing machine INSTRON 1342. The geometrical and mechanical parameters of the specimen as well as the loading speed and the boundary conditions used in the numerical simulations are set equal to that used in the experiments. Fig. 2 shows the results obtained by the experiments and the corresponding simulations, from which it can be clearly seen that the experimental deformed configuration is in agreement with that resulting from the numerical simulation, as shown respectively in Fig. 2(a–d), for two values of compression ratio ε, i.e. $\varepsilon = 0.3$ and $\varepsilon = 0.6$. In this study the mean stress is defined as $\sigma = F/A$, in which F is dynamic force acting on the honeycomb surface area A. It should be pointed out that for oblique loading conditions, A changes gradually during the compression. Thus, σ represents the nominal stress calculated with reference to the initial area A_0. The experimental curve representing the dynamic response in terms of mean stress as a function of the compression ratio depicted in Fig. 2(e) shows an excellent agreement with the numerical one. Fig. 2(f) presents the internal energy absorption and the hourglass energy obtained by simulation, as well as the energy absorption obtained by experiment as a function of the compression ratio, from which a perfect coincidence can be clearly observed. Additionally, the amount of the hourglass energy remains very small compared to the internal energy, thus confirming the validation of the obtained numerical results.

In addition, the simulated in-plane dynamic response under a aligned compressive load (i.e. at a zero inclination angle) for X_1 and X_2 directions (shown in Sections 3.1 and 3.2) is consistent with that presented in Ref. [15], providing a further validation of the numerical model developed in this work.