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Graded square honeycomb as sandwich core for enhanced mechanical performance

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ABSTRACT

Honeycomb as sandwich core construction has been established as one of the best candidates among ultralight cellular materials for load-bearing and energy absorption applications. In this paper, by introducing non-uniform mass distribution (gradient) in the core, substantially improved structural performance of a fully-clamped sandwich plate with square honeycomb core is achieved for out-of-plane uniform pressure loading. In-plane gradient of core is defined and achieved via two approaches: web thickness variation and cell size variation. Response of sandwich plates with linear in-plane core gradient is systematically investigated with finite element (FE) simulations. For both quasi-static and blast loading cases, it is found that positively graded cores exhibit advantage in stiffness, strength as well as plastic energy dissipation compared to cores without gradient or with negative gradient. Examination of plastic energy dissipation in a graded core reveals that ribs placed next to its symmetry plane are more sensitive to changes in thickness or location compared to those placed adjacent to the clamped edges. With the total mass of the core constrained, the constituent material can be more efficiently utilized by either increasing the thickness of ribs close to symmetry planes or moving ribs towards the symmetry planes.

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1. Introduction

The relationship between mechanical performance and structural or micro-structural topology has attracted a great deal of attentions of researchers in the field of engineering designs from natural materials [1] to engineering materials [2,3]. In the same way, the mechanical performance of a sandwich structure, such as stiffness and strength, is largely dictated by how its core is designed [4–6]. Among a multitude of two- and three-dimensional cellular cores, regular honeycombs have been identified as one of the most promising candidates for ultra-lightweight sandwich constructions [4,7]. To further enhance the structural performance of honeycomb sandwich structures, this study proposes to introduce the concept of in-plane gradient into the honeycomb core.

Introducing gradient into a cellular material has attracted much recent attention [8–11]. By varying honeycomb cell thickness, Ajdari et al. [12] investigated the influence of gradient upon the crush behavior and energy absorption of honeycombs with either regular or irregular cells under in-plane compression at constant velocities. When the porosity of the honeycomb increases along the direction of crushing, its energy absorbing capacity is enhanced. By varying cell size along the direction of impact, Wang et al. [13] introduced linear density gradient to honeycombs and found that arranging low relative density (or, equivalently, large porosity) at the impact side can better protect the impacting object. Similarly, core design with gradient is found to bring benefits to a multitude of sandwich structures subjected to shock or blast loading, including beams [14,15], plates [16], hollow barrels [17] and spherical shells [18]. Shen et al. [19] studied the impact behavior of a graded cellular rod and observed the "Double shock" phenomenon. Subsequently, this phenomenon was analytically modeled and numerically validated using graded honeycombs and foams [20,21].

In most existing studies as discussed above, the gradient that has been considered for cellular materials is parallel to the direction of external load, e.g., two-dimensional (2D) foams or prismatic honeycombs with in-plane gradient subjected to in-plane compressive loading. The case where the core gradient is perpendicular to loading direction is much less investigated. Recently, Xu et al. [22] fabricated lattice-cored sandwich beams with core gradient along beam span and studied its performance under three-point bending. It was found that the presence of core gradient has remarkable influence upon the strength and failure modes of the sandwich beam, which could be optimized according to load intensity. However, little is known about the influence of "in-plane gradient" on the response of honeycomb-cored sandwich structures loaded in the out-of-plane direction.

In this study, the mechanical behavior of a fully-clamped metallic sandwich plate with graded square honeycomb core subjected to uniform pressure over its top face sheet is investigated. Both quasi-static

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and dynamic (blast) loading cases are considered. The former is an important issue in engineering applications because a plate quasi-statically loaded with pressure could represent scenarios such as a gate/wall subjected to wind loading or a roof loaded by heavy snow. The latter corresponds to pressure loading with much higher amplitude, occurring within a very short time interval, e.g., blast loading. The gradient is introduced to the honeycomb core in the form of either cell size or web thickness variation, as illustrated schematically in Fig. 1. The stiffness and strength of a graded sandwich plate as well as plastic energy dissipation in each of its constituent are numerically calculated and compared with those of conventional ungraded (uniform mass) honeycomb sandwich.

2. Square honeycombs with in-plane gradient

Consider first the mechanical performance of an edge-clamped square metallic sandwich plate with square honeycomb core (made of orthogonal ribs) subjected to quasi-static uniform pressure loading on its top face sheet (Fig. 1c). As for most conventional sandwich structures, the separated face sheets lead to a larger section inertia moment, resulting in improved resistance to bending moment caused by the applied pressure, while the core is designed primarily to sustain the shear force. In the present study, two approaches to rearrange the distribution of mass in the honeycomb core are explored: (1) web thickness variation and (b) cell size variation, as shown in Fig. 1a and b. For the former, as orthogonal ribs with different thicknesses are assembled to form the honeycomb core, the web thickness of each cell is no longer uniform compared to honeycombs without gradient. For the latter, identical ribs are unevenly spaced and assembled, resulting in rectangular shape and non-uniform size of honeycomb cells.

For reference, the relative density of a conventional (ungraded) square honeycomb core can be expressed in terms of its web thickness t_0 and cell size B_0 as:

$$\overline{\rho}_{c0} = \frac{2t_0B_0 - t_0^2}{B_0^2} \approx \frac{2t_0}{B_0}. \tag{1}$$

Correspondingly, the areal mass of a sandwich plate with ungraded core is:

$$\overline{M} = (2h_f + \overline{\rho}_{c0}H)\rho_s \tag{2}$$

where h_f and H denote face sheet thickness and core height, respectively, and ρ_s is the relative density of the constituent material.

Let t and B denote separately the web thickness and unit cell size in a graded honeycomb core. Non-uniform mass distribution in the core causes its relative density to vary in the plane of the sandwich plate. In this case, the in-plane gradient of the core may be defined as:

$$g_\alpha(x, y) = -\frac{\Delta(t/B)}{\Delta(\alpha/L)}, \quad \alpha = X, Y \tag{3}$$

where (X, Y) denote the distance between the cell and plate center, and L is the span from plate center to clamped edges. Due to the orthogonal nature of the honeycomb core, its mass distribution is uniquely determined by gradients along X and Y directions. For simplicity, the present study considers only the case where the mass in the honeycomb core is distributed in the same manner along X and Y directions (i.e., $g_X = g_Y \equiv g$). Further, only constant in-plane gradient is considered, i.e., the relative density of the core varies linearly along X and Y directions (Fig. 2). Consequently, one constant quantity g is sufficient to quantify the non-uniform mass distribution in the present graded honeycomb core.

Take the X direction as an example. Let X_n, t_n and B_n denote separately the distance to plate center, web thickness and cell size of the n-th cell from plate center. X_n and B_n then satisfy:

$$X_n = \begin{cases} \frac{1}{2}B_n & n = 1 \\ X_{n-1} + \frac{1}{2}(B_n + B_{n-1}) & n > 1 \end{cases} \tag{4}$$

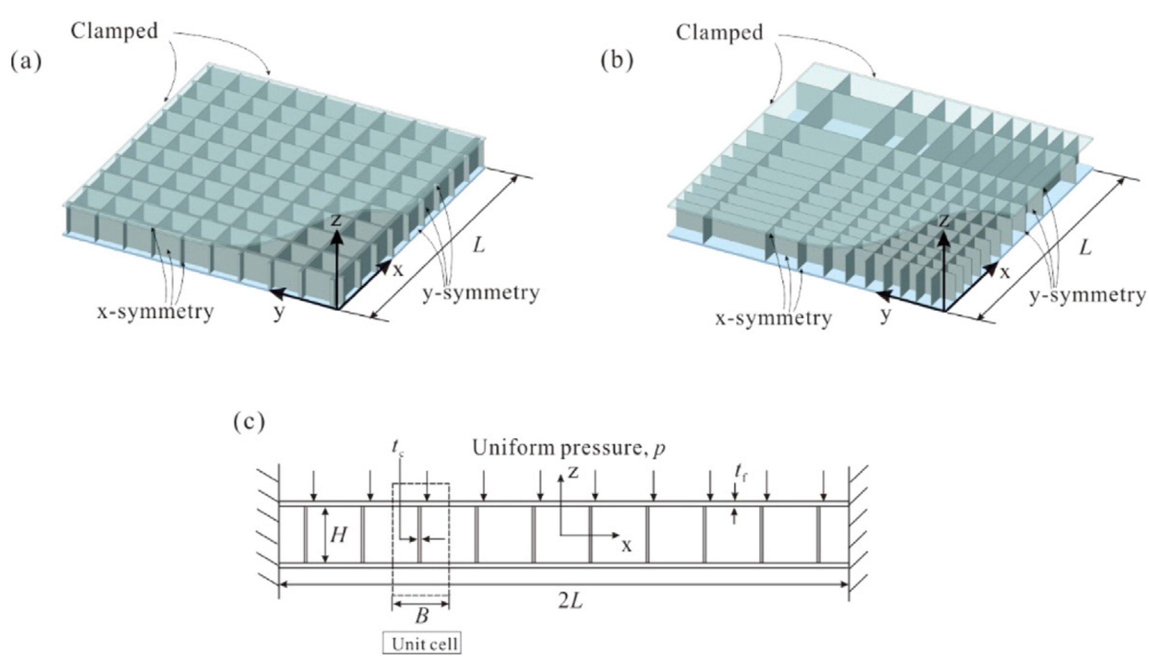

Fig. 1. (a) Honeycomb-cored sandwich plate with varying core web thickness, (b) honeycomb-cored sandwich plate with varying cell size, and (c) fully-clamped, honeycomb-cored sandwich plate (ungraded core shown for simplicity) subjected to out-of-plane uniform pressure.

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