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Mechanical performance and energy absorption properties of structures combining two Nomex honeycombs

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ABSTRACT

To study the mechanical performance and energy absorption property of two-layer Nomex honeycombs of different types, compressive tests on different combinations were conducted and the experimental results compared with those from tests on single honeycomb specimens. The types of combinations include combinations of two honeycombs of the same specification without a clapboard (HSSWC), combinations of two honeycombs of the same specification containing a clapboard (HSSCC), combinations of two honeycombs of different specification without a clapboard (HDSWC), and combinations of two honeycombs of different specification containing a clapboard (HDSCC). The results showed that different combinations were suitable for different situations. It was advisable to apply the combinations containing clapboards as crashworthy structures which call for large collapse stress. It is necessary to reduce the initial collapse stress in the damping and energy-absorbing structures, so combinations without clapboards can be used. The structures combining different honeycomb specifications can be adopted to control the ordered deformation and ladder energy levels.

1. Introduction

Nomex honeycombs are biomimetic honeycomb cores made from poly fibre (m-phenylene isophthalamide). They have high specific strength and stiffness, good corrosion resistance and fire resistance, unique rebound resilience and shock absorption, good electromagnetic wave permeability, high-temperature stability, etc. [1–3]. At present, Nomex honeycombs, as a type of composite material, are widely used in airframes, ships, and high-speed trains. Additionally, exhibiting excellent damping and energy absorption performance, Nomex honeycombs can be used as special damping and packaging materials, and as special energy-absorbing structures [4–6].

At present, honeycomb materials used for damping mainly include paper, aluminium, and Nomex honeycombs. As for paper honeycombs, Zhi-Wei Wang et al. [7] demonstrated the energy absorption properties of paper honeycombs, and found that yield strength of each corrugated medium changed slightly, when the relative humidity was smaller than 75%, but decreased significantly in humid environments. Dongmei Wang et al. [8] evaluated the dynamic impact behaviour of many types of paper honeycombs. The damping properties of the structures increase with cell-wall thickness, cell-wall length, and density of honeycomb cores. For aluminium honeycombs, many studies [9–11] have been conducted on the buckling and post-buckling processes in transversely-loaded aluminium honeycombs using both experimental and numerical approaches. These aluminium honeycomb structures also exhibit prospects for broad application in various crashworthy buffer structures [12,13]. With regard to the optimum design of a sandwich panel, Catapano and Montemurro [14,15] proposed a multi-scale approach for the optimum design of sandwich plates with a honeycomb core. The numerical examples proved that a significant weight saving could be obtained. Montemurro et al. [16] dealt with the problem of the optimum design of a sandwich panel based on a multi-scale numerical optimisation procedure. The results also showed that a significant weight saving could be obtained. Heller and Gruttmann [17] proposed a two-scale computational model, which could describe local effects of non-linearity such as face sheet buckling or plastic flow, for sandwich composites with a comb-like core structure. An et al. [18] performed optimal design of composite sandwich structures by involving both discrete and continuous variables meanwhile integrating all structural cases into a single problem formulation. Zhang et al. [19] investigated the out-of-plane crashworthiness of bio-inspired hexagonal hierarchical honeycombs (HHHs). They found that HHHs had higher specific energy absorption and crushing strength. Yasui Yoshiaki [20] revealed the dynamic and quasi-static crushing behaviour of single and multi-layer

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honeycomb panels, and found that the energy absorption performance of the pyramid type was better than that of the uniform type. Fazilati and Alisadeghi [21] optimised a multi-layer honeycomb energy absorber, and found that the energy absorption performance could be improved by using the multi-layer configuration and increasing the number of layers. Wang et al. [22] studied mechanical behaviour of a composite structure filled with tandem honeycombs and found that the tandem honeycomb structure performed better and showed a stable, rectangular-like compression history after pre-compression. Eskandarian et al. [23] validated a surrogate test vehicle for impacts with roadside objects. The bogie was equipped with a multi-compartment impactor made of multi-layer aluminium honeycombs. With respect to Nomex honeycombs, Heimbs et al. [24] investigated the effect of loading rate on Nomex honeycombs and found that the stress increases by up to 30% as the strain rate changes from $10\,s^{-1}$ to $300\,s^{-1}$. Foo et al. [25] used the fundamental mechanical properties of Nomex paper in the finite element modelling, and proposed that the Young's modulus of the bare honeycomb, as obtained numerically, matched the experimental values. Heimbs [26] compared numerical and experimental results for Nomex honeycomb cores and other structures. The models were designed to allow complete mechanical characterisation. Liu et al. [4] conducted tensile and compressive tests to study the mechanical response of the Nomex honeycomb core under transverse loading. They found that the volume of the resin coating exerts a positive effect on the collapse strength of the honeycomb core. Bunyawanichakul et al. [27] focused on high-load-bearing capacity inserts made of a resin moulded in the Nomex sandwich core. They carried out pull-out tests and analysed the non-linearity and failure modes thereof.

In summary, Nomex honeycomb's abilities in energy absorption and environmental resistance are stronger than those of paper honeycomb [7,28], and its cycling processability and specific energy absorption are better than those of aluminium honeycomb [29,30], but as a crashworthy material, the single Nomex honeycomb has the following shortcomings: (1) the initial stress peak is large, so as a buffer material, it is harmful and does not protect the safety of people and goods; (2) the stability of impact force therein is poor; (3) when the requirements of compression stroke are large, the single honeycomb is prone to buckling instability and the energy absorption effect is reduced; and (4) considering the unique processing technology used in Nomex honeycombs, excessive thickness in the product may lead to high production costs. The above shortcomings have seriously constrained the Nomex honeycomb from becoming an excellent buffer material, therefore the honeycomb structure should be improved in a certain way. Meanwhile, an excellent energy-absorbing structure is supposed to be equipped with the performance of multi-stage stress. It is clear from Refs. [20–23] that the aluminium honeycombs achieve the requirements through the combinations of buffer structures of multi-stage gradient. However, no study about the combination of Nomex honeycombs has been found in the literature so far. Due to the great differences in the performance between Nomex honeycomb and aluminium honeycomb, this work will investigate the mechanical performance and energy absorption properties of different types of Nomex honeycombs combined through different methods by conducting compressive tests. The results and conclusions can provide data relating mechanical performances for application and performance improvement of Nomex honeycombs.

2. Materials and experimental methods

2.1. Materials and definition

The Nomex honeycombs are made of 722 aramid fibre purchased from DuPont Company in the United States. Fig. 1 illustrates a typical Nomex honeycomb specimen and its structural parameters. The Nomex honeycomb shows typical honeycomb core structure with double-walled cells and L, W, T, t, l, and h, d, and θ refer to the length, width, thickness of the honeycomb, wall thickness, side length, diameter of honeycomb cells ($d = 2l\cos\theta$) and cell wall angle, respectively. As for the honeycomb cell with a regular hexagonal shape, $l = h$, $\theta = 30^\circ$, and $d = \sqrt{3}\,l$. The basic material of the honeycomb core is phenolic resin-impregnated Nomex aramid paper and the cell wall is essentially a laminated structure owing to its manufacturing processes (as shown in Fig. 1(c)). Fig. 1(d) shows the stress-strain curve of a typical Nomex honeycomb along the out-of-plane T-direction, which includes three phases: elastic deformation, stable collapse deformation (plateau), and densification phases.

In general, manufacturers define the specification of their honeycombs according to honeycomb type, size and shapes of holes, and equivalent density. The equivalent density ρ_n of a honeycomb core is obtained by dividing the mass by the volume. Here, the three most widely applied Nomex honeycombs (1.83-48, 2.75-32, and 2.75-48) were used to study combinations thereof, and Table 1 shows the geometrical parameters of those honeycombs tested. Among them, 1.83 and 2.75 are the side lengths of the honeycomb cell, and 32 and 48 are the equivalent densities of the honeycomb core.

Fig. 2 shows the structural specimens of the four combinations. Fig. 2(a) demonstrates the combination of two honeycombs of the same specification without a clapboard (HSSWC) and the structure is directly superimposed by two honeycombs with the same specification and section size. Moreover, the two directions of the two honeycombs are vertically arranged (namely, the L-direction of one honeycomb is vertical and normal to that of the other honeycomb). Fig. 2(b) indicates the combination of two honeycombs of different specifications without a clapboard (HDSWC), which is the superposition of two honeycombs with different specifications but the same section size. The two directions of the two honeycombs are also vertically disposed. Fig. 2(c) illustrates the combination of two honeycombs of the same specification containing a clapboard between two honeycombs (HSSCC) whose mode of combination is the same as that of HSSWC shown in Fig. 2(a). The difference of the two combinations lies in the two superimposed honeycombs in Fig. 2(c) being separated by thin aluminium sheets ($102 \times 102 \times 0.8$ mm) each with a mass of 19.5 g. Moreover, the honeycombs are bonded to the sheets by epoxy resin adhesive. Fig. 2(d) indicates the combination of two honeycombs of different specification containing a clapboard between two honeycombs (HDSCC) and the mode of combination is the same as HDSWC in Fig. 2(b). The disparity lies in the fact that two honeycombs are separated by thin aluminium sheets ($102 \times 102 \times 0.8$ mm) and the honeycombs are bonded to the sheets using epoxy resin adhesive.

Table 2 lists experimental schemes and types of combined structures. The combination designation 1.83-48-S-2.75-32 in the table means the combination of two Nomex honeycombs (1.83-48 and 2.75-32) without clapboards while 1.83-48-SP-2.75-32 represents the combination of two honeycombs (1.83-48 and 2.75-32) containing a clapboard between two honeycombs. The single honeycomb is an entire Nomex honeycomb, and its thickness is equal to the total thickness of the combined structures. To avoid the influence of accidental factors on test results, two replicates of all experiments were run for each scheme (a total of 30 experiments were conducted for the 15 schemes).

To study the mechanical performance and energy absorption capacity of different specifications of honeycombs, this research introduced the following main indices for assessment: the compressive stress σ of honeycombs, compressive strain ε in honeycombs, collapse stress σ_c, collapse strain ε_c, plateau stress σ_p, energy absorption E_a, specific energy absorption E_m, and residual rate μ [31].

(1) Compressive stress σ

This research investigated the change of compression stress in three orthogonal directions of the Nomex honeycombs with compressive strain. The compressive stress σ of the honeycomb structure in a certain direction refers to the ratio of the compression force F to plan area A_S in this direction [32].