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Strain rate effect on the out-of-plane dynamic compressive behavior of metallic honeycombs: Experiment and theory

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ABSTRACT

Many studies reveal that the dynamic compressive strength of metallic honeycombs is higher than the quasi-static one, but the reasons for that are still debatable. This paper aims to study the strain rate effect of parent materials on the out-of-plane dynamic compressive behavior of metallic honeycombs. Quasi-static and dynamic tests on aluminum honeycombs were performed with universal testing machine and Split Hopkinson Pressure Bar, respectively. The velocity values of dynamic tests were from about 6 to 19 m/s. The present and existing measures of plateau stress are evaluated by both the rate-independent (R-I) and rate-dependent (R-D) shock theories. It is shown that the R-D shock theory proposed in our previous study provides more accurate predictions at low, medium and high impact velocities. Based on the R-D shock theory, the influences of strain rate effect are analyzed quantitatively and the change tendencies of measured plateau stresses with impact velocities are explained reasonably. The analysis indicates that the strain rate effect has a large contribution to the dynamic enhancement of metallic honeycombs in a wide velocity range.

1. Introduction

Metallic honeycombs are widely used in the packaging, transport and aircraft industries due to their lightweight, high specific stiffness and strength and outstanding energy absorption performance. In these engineering applications, dynamic loadings are often encountered. Under dynamic loading, the response of honeycombs is significantly different from that under static loading [1–13], and honeycomb structures designed with static properties are usually too conservative and wasteful. Much effort has been made on the in-plane dynamic compressive properties of honeycombs [14–19]. However, honeycombs are generally used as core materials of sandwich plates [20], and the out-of-plane stiffness and strength are much higher than those with respect to the in-plane directions [21]. Therefore, it is necessary and important to study the out-of-plane dynamic compressive behavior of metallic honeycombs.

As for the out-of-plane compressive behavior of metallic honeycombs, McFarland [22] provided a semi-empirical expression to predict the plateau stress of hexagonal honeycombs. Since that pioneering study, Wierzbicki [23] developed a more reasonable model as the correct cell wall deformation patterns were identified. Zhang and Ashby [24] proposed a formula for the plateau stress of hexagonal honeycombs with uniform cell wall thickness. Systematic and detailed studies of honeycombs were published in the book of Gibson and Ashby [21]. In the numerical and experimental fields, Aktay et al. [25] simulated the compressive behavior of honeycomb with a meso-structure model and a homogenized model and compared the numerical results with the experimental data. Wilbert et al. [26] presented a comprehensive study of the compressive response of hexagonal honeycombs through experiments and simulations. More recently, Zhang et al. [27] performed simulations and experiments to evaluate the influences of cell number and central angle on the out-of-plane compressive resistance of aluminum honeycombs.

Beside the quasi-static investigations mentioned above, the out-of-plane dynamic compression of honeycombs was also frequently studied, and the compressive strength of honeycombs under dynamic loading has been shown to be higher than that under quasi-static loading [1–13]. The inertia effect has been

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regarded as the main reason for the dynamic enhancement, and a rate-independent (R-I) shock theory considering the inertia effect was proposed to predict the dynamic compressive plateau stress [6,28]. This model has been widely used to evaluate the dynamic enhancement of cellular materials [17,15,29–34]. However, such a model do not account for the strain rate effect of parent materials from which cellular materials are made. More dynamic finite element studies can be found in literature, but most of them adopted a rate independent elastic-perfectly plastic or bilinear constitutive law [8,11,35–37]. Recently, Tao et al. [38] studied the strain rate effect on the behavior of metallic honeycombs through numerical analysis and a rate-dependent (R-D) shock theory was proposed. As the strain rate effect of parent materials is considered to be small and often neglected in the current studies, its influences on the dynamic enhancement are still unclear and the quantitative analysis is not available. Besides, it is observed that the change tendencies of measured plateau stresses are different in the low [12], medium [3] and high [6] velocity ranges, and that also lacks a convincing theoretical explanation. Therefore, more studies need to be done to further understand the out-of-plane dynamic behavior of metallic honeycombs.

In this paper, the strain rate effect on the out-of-plane dynamic compressive behavior of metallic honeycombs is studied through experimental and theoretical investigations. Firstly, quasi-static and dynamic tests on aluminum honeycombs were performed by using the universal testing machine and Split Hopkinson Pressure Bar (SHPB) system, respectively. Secondly, the experimental results are presented and analyzed, and the present and existing measured plateau stresses are evaluated by the R-I and R-D shock theories at low, medium and high impact velocities. Finally, based on the R-D shock theory proposed in our previous study [38], the influences of inertia and strain rate effects are analyzed, and the change tendencies of measured plateau stresses with impact velocities are also explained.

2. Experimental procedures of quasi-static and dynamic tests

2.1. Specimen specification

Typical honeycomb specimens contain 19 complete cells used in this study are shown in Fig. 1. The honeycomb specimens were made of Al3003-H18 with density of 2730 kg/m^3 and elastic modulus of 68.9 GPa. The honeycomb is regarded as an orthotropic material, and the orthotropic directions can be denoted as the L, W, and T directions [39], as shown in Fig. 2(a). The T direction, also called the out-of-plane direction, is paralleled with the axis of the cell wall. The other two directions are referred to in-plane (L and W) directions. The L direction is called the ribbon direction, and the cell wall thickness in the L direction is double that in the width or W direction, which is transverse to the L direction [40].

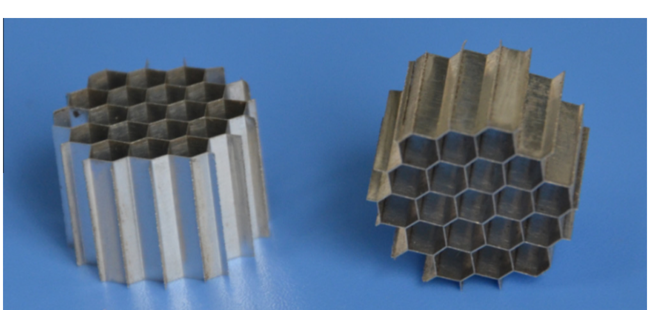

Fig. 1. Typical hexagonal aluminum honeycomb specimens used in this study.

Specimens employed in tests were designed as cylindrical columns with diameter of 20 mm and height of 14 mm. The cell wall thickness t is 0.06 mm and the cell wall length l is 2 mm. All specimens were carefully cut from a big square honeycomb panel using wire electric discharge machining (WEDM). It should be noted that honeycomb specimens with accurate dimensions and little damage can be obtained by taking the advantages of a WEDM method [41,42]. Detailed geometrical configuration of a honeycomb specimen is shown in Fig. 2.

2.2. Experimental arrangement of quasi-static tests

The quasi-static tests were carried out with an electronic universal testing machine (Fig. 3(a)) at a loading velocity of 0.5 mm/min based on both the Chinese test method [43] and the ASTM standards [44–46]. In this machine, the lower platen was stationary, whereas the upper platen was movable towards the lower one. The plane surface of the upper platen was smooth enough to avoid the influences of friction, but the surface of lower platen had circle-shaped notches. It must be noted that the platen-specimen interface friction should be avoided for compression tests [45,46]. Therefore, an iron cylinder with polished upper surface was put on the lower platen. Then the honeycomb specimen was placed on the polished surface in order to minimize friction. Three specimens were tested for this case and mean value of the data was used as the result.

2.3. Experimental arrangement of dynamic tests

The dynamic tests were performed on a SHPB system, which was often used as an experimental setup to study the dynamic behaviors of materials [9–11,31]. The SHPB setup used in this study is illustrated in Fig. 3(b), and its schematic diagram is shown in Fig. 4. It can be seen that a typical SHPB setup is composed of input and output bars with a honeycomb specimen sandwiched between them. A striker bar launched by a gas gun impacts the free end of the input bar and generates a compressive longitudinal incident wave $\varepsilon_i(t)$. When the incident wave arrives at the input bar-specimen interface, part of it is reflected and develops a reflected wave $\varepsilon_r(t)$ in the input bar, while the rest passes through the specimen and develops the transmitted wave $\varepsilon_t(t)$ in the output bar. Based on the strain measured by two gauges, the forces and velocities can be calculated as follows [9–11]:

$$\begin{aligned} &v_{input} = C_0(\varepsilon_i(t) - \varepsilon_r(t)) \quad &F_{input} = S_{bar}E(\varepsilon_i(t) + \varepsilon_r(t)) \\ &v_{output} = C_0\varepsilon_t(t) \quad &F_{output} = S_{bar}E\varepsilon_t(t) \end{aligned} \tag{1}$$

where v_{input}, v_{ouput}, F_{input}, F_{output} are velocities and forces at the bars-specimen interfaces, S_{bar}, E and C_0 are the cross sectional area, elastic modulus and the longitudinal wave velocity of the bars, respectively, $\varepsilon_i(t)$, $\varepsilon_r(t)$, $\varepsilon_t(t)$ are the strain signals at the bars-specimen interfaces.

A range of impact velocities was covered from 6 to 19 m/s by varying the air pressure in the gas gun. It should be noticed that the density of aluminum honeycomb is small, so its impedance is low and the induced strain in an ordinary pressure bar (like steel bar) is too small to measure accurately [9]. In order to get an accurate measurement, the low impedance PMMA bars with diameter of 30 mm were used to match the impedance of aluminum honeycomb specimen. The striker bar had a length of 290 mm, and both the input and output bars were 2000 mm long. The surfaces at the bars-specimen interfaces were lubricated to reduce the influence of friction. Three and five specimens were tested for dynamic tests with velocities of 19.01 and 8.15 m/s, respectively. Six tests were performed for the velocities of 9.68 and 14.62 m/s, respectively. For dynamic tests with velocities of 6.04, 11.16 and 13.52 m/s, four specimens were tested for each case.