Composites Part B 100 (2016) 78–90

Contents lists available at ScienceDirect

Composites Part B

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

Investigation on dynamic penetration of closed-cell aluminium foam using *in situ* deceleration measurement

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ARTICLE INFO

Article history:
Received 8 March 2016
Received in revised form
9 May 2016
Accepted 3 June 2016
Available online 11 June 2016

Keywords:
Aluminium foam
Closed-cell
Deceleration
Impact
Penetration

ABSTRACT

In this work, the experimental study on the resistance of closed-cell aluminium foam to penetration is undertaken by using a novel *in situ* deceleration measurement unit. Most previous experimental studies in the literature only reported final penetration depth and impact velocity and *in situ* measurements of the impact deceleration history are hardly available. For this reason, an instrumented penetrator is designed with an on-board data recorder and accelerometer. This penetrator measures *in situ* rigid-body deceleration and provides a measure for net resistance on the penetrator during the penetration process. Closed-cell aluminium foam specimens that were prepared in this work are grouped into two groups with different densities and gauge length. The specimens were subjected to impact velocities ranging from 40 to 68 m/s. The effects of the impact velocity, nominal strain rate, the specimen's density and strain hardening on the obtained deceleration-time histories are studied in detail. The obtained deceleration-time histories in this work are interpreted with the quasi-static data and the strength enhancement mechanisms of the metal foams. Two deceleration profiles are observed: namely plateau deceleration and increasing deceleration. It is found that at impact velocity above 50 m/s, the effect of strain hardening of the specimen imposes on the penetrator to obtain an increasing deceleration profile. It is found that the inertia effect has a larger influence on the rate sensitivity of the lower density foams compared with the higher density foams. Lastly, this work also presents the effect of the densification of cells on the penetrator's deceleration response.

1. Introduction

Core materials such as honeycomb, open and closed-cell metal foams are different types of material which are the key component of a sandwich panel construction. Honeycomb sandwiched beam [1] provided good energy absorption to shock loading comparing to solid steel beams of equivalent mass. Metal foam panel offers higher bending stiffness than solid steel sheets of the same weight [2], good shock resistance to blast loading [3] and impulse loading [4]. Metal foams are also placed in a curved sandwich panel to resist shock loading [5]. Metal foam core sandwich panels are installed in a vehicle for the purpose of deceleration control of the occupant's pelvis [6] during a collision and improve the safety of the passengers. In such scenario, the threshold of a colliding object which does not incur damage would be defined as damage tolerance, which is the largest acceleration or deceleration of an object can tolerate [7].

When metal foams are subjected to impact, such as compression or penetration, the resistance of the metal foams is enhanced by the dynamic loading. Strain rate, inertia and stress wave are widely discussed as the dominant effects for the different dynamic strength enhancement. Over the past two decades, several research groups mainly investigated the dynamic response of closed-cell aluminium foams under compression [8–16], while a limited number of indentation or penetration test [26,28,29] were performed. Compression tests have been conducted to determine the strain rate effect on the deformation mode and plateau stress of closed-cell aluminium foams to the applied strain rate in the range of 1×10^{-1} s^{-1} to 1×10^{1} s^{-1} [8] by the use of a universal testing machine (UTS), whereas in the range of 1×10^{-3} s^{-1} to 2.2×10^{2} s^{-1} [9] and from 1×10^{-3} s^{-1} to 4.5×102 s^{-1} [10] by the use of a UTS controlled by servo hydraulic system to achieve a near constant and high strain rate.

For the investigation of the dynamic response of closed-cell aluminium foams at higher strain rate, split Hopkinson bar (SHPB) and direct Hopkinson bar test up are most widely used. In

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http://dx.doi.org/10.1016/j.compositesb.2016.06.040
1359-8368/

SHPB test, depending on the bar materials and configurations, different strain rates were obtained and seek to achieve different objectives. Viscoelastic bar [11], magnesium alloy bar [12], and hollow aluminium tube bar [13] were used as Hopkinson pressure bar to match the low mechanical impedance of closed-cell aluminium foams and increased the amplitude of the strain signal measured by the strain gauges attached to the bar. To overcome the small specimen and small strain level conducted using SHPB, a novel modified SHPB configuration [14] used 50 mm diameter aluminium tubular bar with long pre-stress bar that replaced the striker bar that was typically used in SHPB test to obtain a specimen strain up to 50% due to the generated long-duration pulse. This configuration enabled large diameter of closed-cell aluminium foam that represent the averaged mechanical properties of the material to be tested and attaining force equilibrium at the two specimen ends.

Direct Hopkinson bar test [15–20], which consists only the incident bar has been conducted by several authors to attain higher impact velocity and study the foam specimen's inertial/velocity sensitivity. Two different configurations of Direct Hopkinson bar test are shown in Fig. 1. In one configuration, namely direct-impact test, launches a foam specimen attached with a backing mass and impact on the incident bar. This naming is to standardize the terms used among different authors [15–20]. In the direct-impact test, a foam specimen may be subjected to shock loading under relatively high impact velocity; strength enhancement occurs and leads to a shock front being developed in the specimen. In this configuration, the strain gauges on the incident bar measure the stress and particle velocity behind of the shock front of the deformed specimen as depicted in Fig. 1. The direct-impact test conducted by Deshpande and Fleck [15] related the average strain rate to the obtained plateau stress and concluded that the tested specimens were not rate sensitive up to nominal strain rate of 5000 s^{-1}. In their test, the dynamic plateau stresses of the specimens were obtained at 10% nominal axial strain, and the nominal strain rate was obtained by the measured impact velocity divided by the specimen fixed length of 10 mm.

In a later paper, Tan et al. [16] attempted to clarify the conflicting conclusion between the relationship of nominal strain rate and dynamic strength. For example, a nominal strain rate of 5000 s^{-1} can be obtained either with an impact velocity of 50 m/s and a specimen length of 10 mm or an impact velocity of 100 m/s and a specimen length of 20 mm. Therefore, Tan et al. [16] conducted direct-impact test using various lengths of the closed-cell aluminium foam specimens and impact velocities to differentiate the rate sensitive response of the specimens due to an increase in the impact velocity or nominal strain rate due to the specimen length. His results showed that the dynamic strength of the specimens was dependent on the impact velocity, especially at high impact velocity. The dynamic strength of the specimens were well predicted by a 1D 'shock' model proposed by Reid and Peng [17] and shown in Eq. (1).

$$\sigma_d = \sigma_{pl}^{qs} + \frac{\rho_0 V^2}{\varepsilon_d} \tag{1}$$

where ρ_0 is the initial foam density, V is the impact velocity, ε_d is the densification strain, σ_{pl}^{qs} is the plateau stress, superscript, qs and subscript, pl in σ_{pl}^{qs} , denote quasi static and plateau respectively. This shock model represents a rigidly perfectly plastic lock (RPPL) idealization to explain the inertia effect on the dynamic plateau stress, σ_d. Tan et al. [16] concluded there is no correlation between the nominal strain rate and the dynamic strength of the specimen.

Another configuration of the direct Hopkinson bar tests, namely reverse-impact test, launches a striker bar on a foam specimen attached to a Hopkinson bar. In the reverse-impact test, the strain gauges on the incident bar measure the stress and particle velocity ahead the shock front of the deformed specimen [18] as illustrated in Fig. 1. Wang et al. [19] attached semiconductor strain gauge near the impacted end of the incident bar to measure real-time stress travelling pass through it. He selected two specimens of similar density and dimension; each specimen subjected to either direct-impact or reverse-impact test with similar impact velocity. The results showed at increasing impact velocity, the difference between the stress profiles obtained from the direct-impact and reverse-impact test became larger. At relatively low impact velocity, the small difference between the stress profiles indicated the specimen was under equilibrium state, and stress fields were uniformly distributed within the specimen. In this condition, the strain rate effect was solely responsible for dynamic strength enhancement. However, at relatively moderate impact velocity, the appreciable difference between the two stress profiles indicated the strain-rate and inertia effect were important. Lastly, at relatively high impact velocity, the significant difference of the two stress profiles showed that the inertia effect dominated the strength enhancement of the specimen. Hence, the direct-impact and reverse-impact tests can distinguish the different strength enhancement effects and the critical velocities that transition to different strength enhancement regime. While Tan et al. [16]

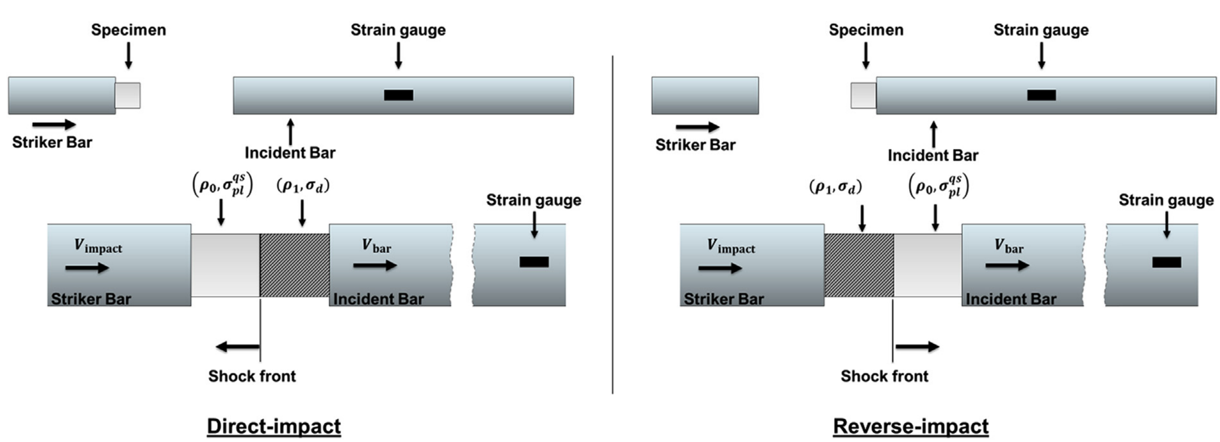

Fig. 1. Two configurations of Direct Hopkinson bar test. Parameters defining a foam specimen under shock loading: ρ is density and the suffixes 1 and 0 refer to conditions behind and ahead of the shock front, σ_d is dynamic stress and σ_{pl}^{qs} is quasi-static plateau stress.