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Propagation of a stress wave through a virtual functionally graded foam

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Dedicated to Professor Philippe Boulanger on the occasion of his 60th birthday.

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ABSTRACT

Stress wave propagation through a Functionally Graded Foam Material (FGFM) is analysed in this paper using the finite element method. A finite element model of the Split Hopkinson Pressure Bar (SHPB) is developed to apply realistic boundary conditions to a uniform density foam and is validated against laboratory SHPB tests. Wave propagation through virtual FGFMs with various gradient functions is then considered. The amplitude of the stress wave is found to be shaped by the gradient functions, i.e., the stress can be amplified or diminished following propagation through the FGFMs. The plastic dissipation energy in the specimens is also shaped by the gradient functions. This property of FGFMs provides significant potential for such materials to be used for cushioning structures.

1. Introduction

Cellular foams are widely used in energy absorbing applications where it is important to minimise the peak acceleration of the impacting body [1], e.g., packaging of fragile goods, protective headgear [2,3] and body garments. This is due to their low volume fraction of solid material and their complex microstructure which allows large degrees of plastic crushing to occur at a fairly constant stress value. This plastic crushing at a constant stress will continue until, depending on their initial density, a densification strain is reached when cell walls and struts impinge on one another and further crushing is of the material matrix itself rather than the foam cells. Understanding their dynamic stress–strain behaviour at finite deformations is therefore essential in order to predict their performance as cushioning materials.

Much research has been performed, both experimentally and numerically, on the finite deformation of both polymeric and metallic foams under quasi-static to moderate strain rate conditions. However, there does not appear to be an obvious consensus in the literature as to the dynamic behaviour of metallic foams w.r.t. strain rate sensitivity. Deshpande and Fleck [4] reported that the plateau stress in closed cell Alulight and open cell Duocel metallic foams is almost strain rate insensitive, up to rates of 5000/s. An open celled AA6101-T6 AL foam was investigated by Lankford and Dannemann [5], who reported almost no change in mechanical strength in response to varying strain rates. Peroni et al. [6] also reported strain rate insensitivity for aluminium foam. However, Kanahashi et al. [7] have investigated the dynamic strain rate response of open celled SG91A aluminium foam at a rate of 1400/s and reported a strain rate dependence. Dannemann and Lankford [8] reported a strain rate effect in closed cell ALPORAS foam at strain rates between 400 and 2500/s. They noted that strain rate effects were higher for a higher density and attributed this to the kinetics of internal gas flow. El-nasri et al. [9] reported a limited rate sensitivity for ALPORAS foam at strain rates up to 1300 m/s. Zhao and Abdennadher [10] stated that the rate sensitivity of metallic foam is due to inertia effects in dynamic buckling of cell walls, even though their foam was made of strain rate insensitive material. Klintworth [11] and Reid and Peng [12] discussed the possibility for the strength increase in cellular structures whereby, under dynamic conditions, the collapse mechanism of the foam changes from a quasi-static mode to a dynamic mode involving additional stretching of the cell wall that dissipates more energy. Therefore, the additional micro-inertial contribution from the additional stretching of all cell walls can lead to the observed strain rate response.

The recently emerging field of Functionally Graded Materials (FGMs) was initially limited to metal–ceramic composites to combat high thermal gradients in the aerospace industry, but can also be applied to cellular structures. It has already been shown numerically [13] that Functionally Graded Foam Materials (FGFMs) are suitable candidates for providing improved energy absorbing properties over those provided by conventional foams of uniform densities. Bruck [14] has studied FGMs to analyse the effect of a gradient architecture on the mitigation of stress waves reflected from the graded interface. Berezovski [15] extended the study of stress wave propagation from one dimension to two dimensions for metal–ceramic FGMs. The current study examines wave propagation through a virtual FGFM, using a traditional Split Hopkinson Pressure Bar (SHPB)

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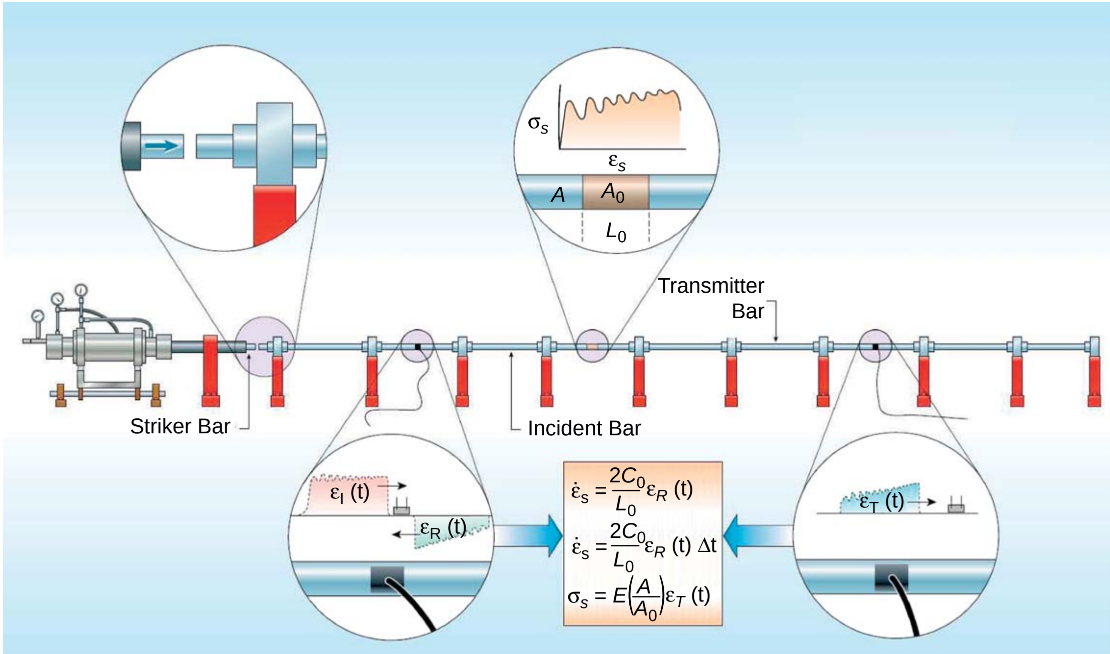

Fig. 1. Schematic illustration of the Split Hopkinson Pressure Bar (SHPB) [19].

setup to apply meaningful boundary conditions, and to elucidate the general energy absorbing mechanisms of this type of material. Metallic foam, rather than polymeric foam, was used in the current study as the former has higher impedance.

Manufacturing a FGFM is inherently more complex than a uniform foam due to the varying material properties; however, some authors have reported on technologies to produce such materials. Brother and Dunand [16], for example, created density graded aluminium foams from polyurethane foam precursors using an investment casting method. This was in an effort to improve mass efficiency in load bearing metallic foams. Matsumoto et al. [17] have proposed an alternate and interesting method to produce density graded foams: rather than introducing the gradient at the time of foaming, their method is based on chemical dissolution of a uniform foam. By immersing the uniform foam within a NaOH bath of controlled pH and then draining the NaOH by gravity at a constant rate, they introduced a continuous gradient in exposure time of the solution to the uniform foam, thereby creating a continuous density gradient. Kieback et al. [18] also developed a metallurgical process for FGMs which were formed through graded metal powder compacts and followed by melt processing. As described by Kieback et al. manufacturing FGMs on a laboratory scale has reached a considerable level of maturity; however, there will be new challenges including manufacturing processes to mass production and up-scaling, and cost-effectiveness of production processes. The technology to manufacture the functionally graded polymeric foam material is presently being developed in our laboratory and will form the basis of a future publication.

The SHPB was designed to capture the dynamic stress–strain response of materials at very high strain rates. A typical arrangement of the SHPB is shown in Fig. 1. A stress pulse, generated by the impact of the striker bar onto the incident bar, travels down the incident bar and interacts with the specimen. Some of this stress pulse is transmitted through the specimen to the transmitter bar, and some of the pulse is reflected back to the incident bar. Strain gauges, mounted on the incident and the transmitter bars, record the incident strain, $\varepsilon_I(t)$, the transmitted strain, $\varepsilon_T(t)$, and the reflected strain, $\varepsilon_R(t)$, of these two bars. The stress–strain response, $\sigma_s(t)$ and $\varepsilon_s(t)$ (and the strain rate of the response, $\dot{\varepsilon}_s(t)$), of the specimen can be reconstructed from these strain-time records by applying the well-known equations:

$$\dot{\varepsilon}_s(t) = -\frac{2C_0}{L_s}\varepsilon_R(t) \quad (1)$$

$$\varepsilon_s(t) = -\frac{2C_0}{L_s}\int_0^t \varepsilon_R(t)\,dt \quad (2)$$

$$\sigma_s(t) = E_b\frac{A_b}{A_s}\varepsilon_T(t) \quad (3)$$

where C_0 is the wave speed within the bar, L_s is the length/thickness of the specimen, A_s and A_b are the cross-sectional area of the specimen and the bar, respectively, and E_b is Young's modulus of the bar.

The SHPB technique has proved to be extremely versatile and has grown from its original configuration for compression testing to include tension, torsion and fracture testing [20]. It has been used to characterise the dynamic response of a multitude of materials such as soils [21], composites [22], compliant materials [23] and metals [24]. Foams have also been studied using the SHPB technique [25].

Al-Mousawi et al. [20] provided a good summary of the limitations of using the split Hopkinson technique in dynamic testing, including uniaxial stress distribution through the specimen, bar-specimen frictional forces that can cause radial tractions, and the influence of radial dispersion of the pulse wave through the elastic bars. Sawas [26] acknowledged the limitations on high noise-to-signal ratio and low achievable strain when using metal incident and transmitter bars with complaint specimens like rubbers and foams due to the very high impedance mismatch and short rise time of the pulse wave. They introduced an all-polymeric split Hopkinson bar system to overcome these limitations. Chen et al. [27] noticed the non-homogeneous deformation of the SHPB when using low-impedance specimens, due to the attenuation and slow speed of the wave across the soft material ($\lesssim$500 m/s compared to $\gtrsim$5000 m/s for metals). In order to achieve near identical force–time histories on both faces of the soft specimen, a thin sample should be used and pulse shaping techniques should be employed. Although these