DYNAMIC RESPONSE AND FAILURE OF CELLULAR NETWORKS

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ABSTRACT

Lightweight cellular solids are increasingly used as core materials in sandwich structures not only to increase the *specific stiffness* of structural components but also to impart unique *energy absorption* and *impact mitigation* capabilities, which naturally involve the application of dynamic loads. Today, the advances in processing techniques enable the manufacture of cellular cores to prescribed cell sizes and densities as well as, to a certain extent, desired cellular topologies. In this presentation the results of an experimental study will be discussed in a framework to understand the mechanical response and failure behavior of cellular networks as a function of loading rate and cellular topology. Aluminum foams and honeycombs, as the representative material systems of stochastic and regular topologies, respectively, has been tested at varying high-strain-rates using a modified split Hopkinson (Kolsky) pressure bar system as well as at quasi-static strain rates using a servo-hydraulic testing machine. The mechanical response at high rates of loading has been compared to those obtained at quasi-static strain rates in terms of compressive strength, plateau stress and densification strain. The experimental results that show an increased strain-rate sensitivity of compressive strength in regular topologies and relative insensitivity of plateau stress to the rate of loading will be discussed in detail and the concept of micro-inertia will be used to explain these experimental results. The effect of axial inertia will also be discussed as it tends to be dominant at very high loading rates. In this perspective, distinctive regimes of loading rate will be defined where either micro-inertia or axial inertia becomes dominant in overall dynamic response of cellular networks.

1 INTRODUCTION

Dynamic response of cellular solids is drawing increased attention due their low density as well as excellent shock attenuation and impact energy dissipation capabilities. They find widespread application ranging from protective packaging of delicate components to crash and blast mitigation in automobiles, airplanes and naval structures. Therefore, in recent decade, there has been significant number of studies on a variety of cellular solids that address the various aspects of mechanical response under dynamic loading conditions. In these studies, the dynamic response is generally characterized in terms of peak stress, plateau stress, densification strain and specific energy absorption capacity as a function of material and loading parameters such as the relative density of cellular structure and loading rate (impact velocity, strain rate). However, the rich pool of constituent materials and cellular topologies does not easily allow the generalized assessments on the effects of strain rate. The existence of distinctive regimes in their mechanical response and the data reported for a wide range of loading rates and different failure modes further complicates the interpretation of these results. The present study discusses the rate effects in cellular solids from a perspective that facilitates the understanding of their overall dynamic response. To do so, first, the cellular solids will be classified into several subsets as a function of cellular topology. Then, various dynamic strength enhancement mechanisms will be discussed in a framework that considers both loading rate effects and cellular deformation/failure mechanisms. Based on the experimental results of current study and the data reported in the literature, the role of cellular topology and loading rate will be evaluated in an interconnected manner to understand and classify the rate effects in cellular networks.

2 RATE EFFECTS IN CELLULAR NETWORKS

By definition, the term *cellular solid* comprises a wide set of materials systems where the solid phase is distributed over a volume to form an interconnected cellular network with the remaining space filled by a gaseous phase (air). The cellular networks may have stochastic (e.g., foams) or regular (e.g., honeycombs) topologies depending on the distribution of solid phase. Cellular solids with stochastic topologies have a tendency to exhibit isotropic properties mainly due to random shape and orientation of cells (reminiscent of polycrystals), while those with regular topology usually have anisotropic properties due to the use of elongated prismatic cells in common practice (reminiscent of highly textured polycrystals). Furthermore, depending on the interconnectivity among individual cells they are often classified as open-cell or closed-cell structures. In closed-cell networks, the gaseous phase is completely entrapped within the cell structure and, therefore, may have significant influence on the overall mechanical response particularly at high rates of loading. As will be elaborated in the following, a classification of this type is quite useful when evaluating, and before generalizing, the characteristic behavior of cellular networks under dynamic loadings.

The inelastic behavior of cellular solids is governed mainly by the progressive deformation mechanisms which are strongly controlled by the cellular geometry of the structure (Gibson & Ashby [1], Ashby *et al*. [2], Vural & Ravichandran [3]). When the cellular network is loaded dynamically there are rate effects that can be separated into three categories. The first is due to inherent rate-dependence of the constituent material. The interaction between cellular topology and inherent rate-dependence occurs in an indirect way through highly localized nature of deformation in cellular solids. The strain rate experienced by the cell wall material in narrow bands of localized deformation can be orders of magnitude higher than the nominal strain rate. The effect of this higher strain rate on the flow stress of solid phase can be accounted for by defining a characteristic length scale. For stochastic topologies and in-plane loading of regular topologies, the characteristic length scale can be related to average cell size. For out-of-plane loading of regular topologies (such as honeycombs) either analytical or experimental means can be used to describe a reasonable length scale. It is through this length scale that inherent rate-dependence of overall cellular solid can be accurately predicted considering the influence of cellular topology.

The second of rate effects arises from the dynamic compression of gaseous phase within the cellular network. Although its influence is generally neglected in the analysis of open-cell structures, which offer little internal resistance to the flow of gases, resistance arising from the compression of gaseous phase becomes significant at high loading rates and contributes to the overall rate-dependence of cellular solid (Hinckley & Yang [4], Hilyard [5], Shim & Yap [6]).

The third source of rate effects is related to the inertia of the solid phase in cellular network and it should be evaluated under two subcategories depending on the intensity of dynamic loading. There exists a critical impact velocity (strain rate), beyond which a significant enhancement in dynamic stress is formed due to the formation of shock wave. In this supercritical velocity (shock) regime, the cells near the impact surface are severely compressed to the densification and the crushing stress within this localized region increases as a quadratic function of impact velocity as predicted by structural shock wave models (Reid & Peng [7], Harrigan *et al*. [8], Tan *et al*. [9], Lopatnikov *et al*. [10]). *Axial inertia effects* associated with the dynamic localization of deformation are responsible for the enhancement of dynamic strength properties. Depending on the intensity of axial inertia (impact velocity) the stress in the densified region behind the shock front can attain very high values that may be orders of magnitude above the quasi-static stress. The level of dynamic stress enhancement also determine the propagation velocity of shock front, which increases with densification level at the shock front as a direct consequence increasing slope of Rayleigh line. The effects of cell size, topology and morphological effects are insignificant in the shock regime.

If the impact velocity is in subcritical regime, *micro-inertial effects* may play a dominant role in dynamic stress enhancement. The critical impact velocity essentially defines the boundary between shock and micro-inertia regimes and may vary in a wide range from around 40 to 400 m/s depending on the density and deformation characteristics of cellular structure (Reid & Peng [7], Lopatnikov *et al*. [10]). One should be reminded at this point that the majority of energy absorption applications with cellular solids involve subcritical region. The term *micro-inertial effects* is related to *lateral* and *rotational* inertia of rapidly displacing cell walls within and ahead of the localized deformation band (Honig & Stronge [11]). In each cell, crushing initiates when the stress state equals the collapse stress of the easiest mode of deformation. Micro-inertial stress enhancement is particularly significant in the initiation of cell wall collapse in asymmetric modes such as buckling or kink band formation that corresponds to the initial stress peak in the nominal stress-strain response of cellular solids (Reid & Peng [7], Vural & Ravichandran [12]). In this initial phase, the lateral inertia of cell walls suppresses, in fact retards, the more compliant asymmetric modes of cell deformation and dynamic stress enhancement occurs through the axial compression of cell walls before the asymmetric mode is recovered. As the cells deform in intermediate phase, large changes in geometry decrease the stress to continue deformation. The extent of strain-softening during intermediate phase is greatest for asymmetric modes and least for symmetric modes of cell deformation. Therefore, if micro-inertia increases the compliance to the extent that deformation occurs in a symmetric rather than asymmetric mode, the stresses can be substantially increased in the intermediate phase as well, resulting in dynamic stress enhancement in the plateau region of deformation.

Studies on the dynamic response of cellular solids that are made of strain-rate insensitive materials show that, while the materials with periodic topology (e.g., aluminum honeycombs) are prone to dynamic strength enhancement in longitudinal direction (Goldsmith & Sackman [13], Wu & Jiang [14], Zhao & Gary [15]. Baker *et al*. [16], Harrigan *et al*. [8]), those with stochastic topology (e.g., aluminum foams) are insensitive to the rate of loading (Ashby *et al*. [2], Deshpande & Fleck [17]), suggesting that there exists a close relationship between the cellular topology and micro-inertial dynamic strength enhancement. It should be noted that due to the anisotropy of materials with periodic topology their response to dynamic loading might vary depending on the loading direction. In fact, an argument of this type can also be related to a series of studies on what is called type I and type II structures (Calladine & English [18], Zhang & Yu [19], Tam & Calladine [20], Su *et al*. [21-22], Karagiozova & Jones [23]), which have succeeded in explaining certain anomalies regarding their energy absorbing capabilities under dynamic loading conditions. Those studies, in the simplest terms, discuss that the structures with an *unstably softening* quasi-static load-deflection curve (type II) are much more susceptible to inertia based dynamic strength enhancement than the structures with a *flat topped* load-deflection curve (type I). Thus, within this framework, mechanical response of honeycomb materials in longitudinal direction is reminiscent of type II structures while the response of foams and honeycombs in transverse direction falls into the category of type I structures. This analogy is also supported by the experimental data in the references given above.

It should be emphasized that, in subcritical regime, the dynamic stress enhancement through micro-inertial effects is limited by the constitutive response of the material that make up the cellular solid, it is this inertia that is responsible for the dynamic strength enhancement observed in type II structures. In the supercritical regime at higher impact velocities, axial inertia that is associated with the propagation of shock waves through the cellular structure is effective in stress enhancement and it may dominate the dynamic strength enhancement well above the constitutive capacity of material, this type of inertia may result in dynamic strength enhancement in both type I and type II structures. The present study focuses on the subcritical regime and reports the results of an ongoing experimental program that investigates interaction between cellular topology and micro-inertial stress enhancement in cellular networks.

3 EXPERIMENTAL RESULTS AND DISCUSSION

Experimental program covers the testing of a series of cellular solids with both regular and stochastic topologies. In this program, open-cell aluminum foams are considered to be the representative of cellular solids with stochastic topology while aluminum honeycomb and balsa wood represent the regular topology. Quasi-static tests (from 10^{-4} to 10^{0} s^{-1}) were conducted using a servo-hydraulic testing machine while a modified Kolsky (split Hopkinson) pressure bar was used for high-strain-rate experiments in the range $5x10^2$ - $4x10^3$ s^{-1}. The details of experimental procedure and modified Kolsky setup are as described in Vural & Ravichandran [12]. In this extended abstract, only the results pertaining to balsa wood is presented, while the results of ongoing experiments with aluminum foams and honeycombs will be included during the oral presentation. The microstructure of balsa wood is very close to the honeycomb geometry (Vural & Ravichandran [3]) and therefore is considered to have regular topology.

Figure 1 shows the variation initial peak stress and plateau stress for out-of-plane loading, i.e. parallel to the grains, as a function of both strain rate and initial density of specimens. The post-failure SEM examination of specimen microstructures shows that failure occurs by buckling of cell walls for low density specimens while kink band formation is the dominant failure mode for densities above 180-200 kg/m^3. In Figure 1, one can immediately note the significant increase in initial peak stress as the strain rate increases whereas the data for plateau stress is rather scattered and show no significant rate sensitivity. At high-strain-rates the hardening effect of micro-inertia is not as dominant on plateau stress as on initial failure strength because of the softening effect of stress perturbations as discussed above. Experimental results shown in Figure 1(a) suggest that the outcome of competition between two opposing mechanism, i.e., micro-inertia induced hardening and the softening driven by failure induced stress perturbations, is closely related to the characteristic length scale of failure mode involved. Apparently, the result of this competition slightly favors micro-inertial hardening in low-density region due to the smaller length scale

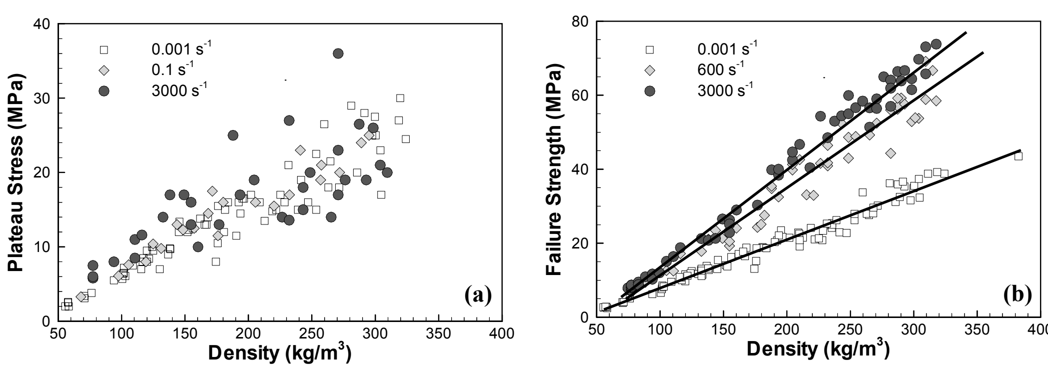

Figure 1: Strain-rate sensitivity of (a) plateau stress and (b) compressive failure strength (initial peak) in balsa wood loaded along the grain as a function of initial specimen density.

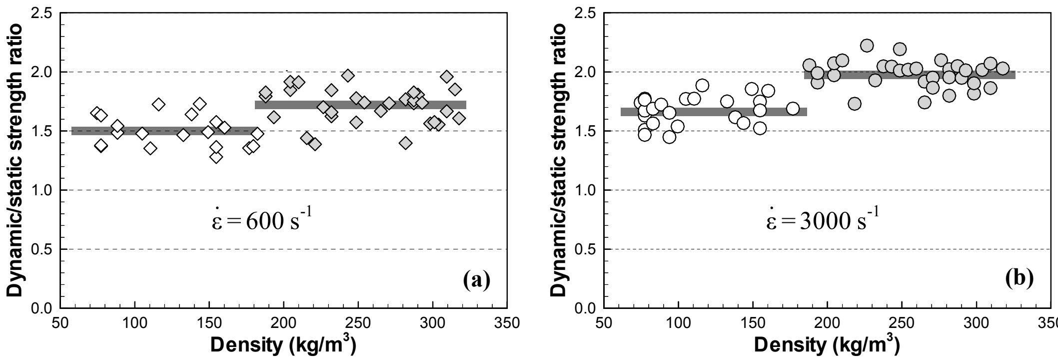

Figure 2: Dynamic strength enhancement (initial peak) in balsa wood as a function of density. Note the apparent effect of failure mode transition from buckling to kink band formation at around 180 kg/m^3.

associated with buckling. On the other hand, for high-density balsa where the cellular structure undergoes failure by kink band formation, inertial effects seem to be suppressed by perturbation softening whose magnitude is higher as proportional to the larger length scale involved.

Figure 2 shows the ratio of dynamic to quasi-static peak stresses for two different high-strain-rates. The jump in data at around 180 kg/m^3 signifies the transition in failure mode from buckling to kink bad formation. It is obvious that the degree of increase in failure strength at high strain rates is different in two subsequent density ranges. For instance, when the strain rate is 3000 s^{-1}, average increase in failure strength over the quasi-static counterpart is around 70 per cent for low density balsa wood where the cellular structure fails by buckling mode. For densities higher than 180 kg/m^3, corresponding increase in failure strength is around 100 per cent and the experimental evidence shows that kink band formation is the operating failure mode in this density range. In a recent study, Vural and Ravichandran[12] discusses about the source of dynamic strength enhancement in balsa wood and attribute it to the micro-inertial effects operating at the cellular scale during high-strain-rate deformation. Using the essential features of failure kinematics for buckling and kink band formation modes, they propose micro-inertia based analytical models that satisfactorily predict the dynamic strength enhancement presented in Figure 2.

4 CONCLUDING REMARKS

Experimental results show that the initial failure strength is very sensitive to the rate of loading for asymmetric failure modes such as buckling and kink band formation. This behavior is attributed to micro-inertial hardening and its dependence on the kinematics of failure mode. In quasi-static loading, these asymmetric failure modes are associated with strain-softening and, therefore, dynamic response is dominated by micro-inertial effects as expected in analogy with Type-II structures. On the other hand, the fact that plateau stress remains relatively unaffected by strain rate is related to the dominance of strain-softening over the micro-inertial effects due to large deformations of cells and resulting stress perturbations during progressive deformation regime. Ongoing study with aluminum foams, with Type-I behavior, are expected to confirm the role of cellular topology in dynamic stress enhancement. It seems that the cellular topology is effective in micro-inertia based stress enhancement to the extent it controls the failure modes of cells.

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