

A Methodology for Characterization of the Strain Rate-Dependent Behavior of PU Foam

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ABSTRACT

Polymeric foams are known to be sensitive to strain rate under dynamic loads. Mechanical characterization of such materials would not thus be complete without capturing the effect of strain rate on their stress-strain behaviors. Consistent data on the dynamic behavior of foam is also necessary for designing energy-absorbing countermeasures based on foam such as for vehicle occupant safety protection. Strain rates of the order of $100\text{--}500\text{ s}^{-1}$ are quite common in such design applications; strain rates of this range cannot be obtained with an ordinary UTM (universal testing machine) and a special test set-up is usually needed. In the current study, a unique approach has been suggested according to which quasi-static tests at low strain rates and low velocity drop tests at medium strain rates are utilized to arrive at an empirical relation between initial peak stress and logarithm of strain rate for a rigid closed-cell PU foam. Using a stress-scaling methodology and the empirical relation mentioned, foam stress-strain curves are obtained for a number of strain rates spanning low (from 0.00033 s^{-1}) to high strain rates (up to 1000 s^{-1}). This data on foam material behavior is expected to be particularly useful in numerical modelling of foam-based countermeasures for impact energy absorption applications.

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INTRODUCTION

Dynamic characterization of foam i.e. finding stress-strain responses at strain rates higher than quasi-static is essential for predicting its behavior in many real-world applications such as energy-absorption under impact loads. However, generating stress-strain data at dynamic strain rates is often a challenging task due to the necessity of specialized equipment such as a Split Hopkinson Pressure Bar [1, 2, 3] which can be expensive and not ordinarily available in an engineering laboratory. This device, despite perhaps being the best resource for ascertaining material behavior at high strain rates, has limitations due to its indirect nature arising from reliance on one-dimensional wave theory for solids, difficulty in performing tensile tests, special material requirements for incident and transmission bars for testing of soft materials such as foam and fibre-reinforced composites, etc. Additionally, the SHPB is generally suitable for strain rates of the order of 1000 s^{-1} or higher [4] although SHPB tests on polymeric foams with acrylic bars have been reported for strain rates in the range of $500\text{--}2500\text{ s}^{-1}$ [5].

Due to the relevance of rigid PU foam for impact safety and packaging applications, attention is paid here toward developing a simple methodology for determining the stress-strain responses of a rigid PU foam at low to medium strain rates. However, it may be pointed out that the methodology adopted is not dependent on the type of foam being considered and can be applied to cellular materials in general. A review of relevant literature indicates that a number of investigators have studied the behavior of polymeric foam under impact loading conditions although desired stress-strain behaviors could not in general be obtained as strain rate does not remain constant in such tests. In fact, in an impact test, strain rate will vary from a maximum value at the instant of impact to zero when the impactor comes to a stop. It is noted that Ouellet, Cronin and Worswick [5] have presented stress-strain curves for polymeric foams directly from impact tests; however, the authors have observed that such data is likely to be inaccurate due to varying strain rate in an impact test. It may be mentioned that a number of investigators have studied the behavior of polymeric foam experimentally under impact loads and carried out numerical simulation to predict the responses and deformation. The influence of strain rate on the mechanical response of

foams was shown in drop-weight [6] and impact sled experiments [7] and was found to be crucial in defining energy absorbing ability. Zhang et al. [8] investigated the impact response of polymer foams using a pneumatically driven impact machine. Kipp et al. [9] conducted studies under high-speed impact conditions. Polyurethane foams have found wide applications in recent automobile bumper designs for impact energy absorption, under vehicle interior trim as occupant impact safety countermeasures, and in shock-isolating encapsulation [10]. Lankford and Dannemann [11] used a drop-weight tower to investigate the dynamic response of elastomeric polymer foams and found their stress-strain behavior to be rate dependent. Progelhof [12] conducted dynamic tests in industry to characterize the impact energy absorption behavior of rigid polymer foams using a drop-weight tower. Faruque, Liu and Chou [13] formulated a strain rate-dependent constitutive model and implemented in an explicit dynamic finite element code developed at Ford Research Laboratory. Chou et al. [14] tested polyurethane foams of varying density under uniaxial compressive loading condition at different rates and temperatures.

As mentioned earlier and revealed through the survey of a cross-section of relevant literature ([14], [15], [16], [17], [18], [19], [20], [21]), methods exist for the determination of stress-strain responses of foam at medium to high strain rates. However, the method discussed here according to which UTM-based tests at low strain rates are supplemented with drop-weight impact tests and a scaling technique has not been reported earlier. In the current study, UTM-based compression tests on cubical samples of a rigid PU foam of a given density (viz. 0.42 gm/cc) and desired mixing ratio of 1:1.1 by volume of polyol:isocyanate are carried out at various low strain rates (by varying cross-head speed). These are then followed up with drop tests on similar specimens in a Versatile Test Rig (named so because of its capability for different types of impact tests). An empirical relation is developed for predicting the initial peak stress of foam using results from low (UTM-based) and medium (corresponding to drop tests) strain rates. A strategy is adopted for developing stress-strain curves at low to medium strain rates with the quasi-static response at a cross-head speed of 1 mm/min as a baseline and applying a scaling approach as explained in the ensuing sections.

LOW STRAIN RATE TESTS

In order to bring out the effect of strain rate on mechanical response of the rigid PU foam under consideration at low strain rates, tests were conducted using a standard servo-hydraulic UTM. Cubical specimens (of size $50 \times 50 \times 50 \text{ mm}^3$) were compressed between compression platens at different loading rates such as 1 mm/min, 50 mm/min, and 300 mm/min, resulting in the global strain rates of $3.33 \times 10^{-4} \text{ s}^{-1}$, $1.67 \times 10^{-2} \text{ s}^{-1}$ and 0.1 s^{-1} respectively which can be considered as low strain rates. It is noted that strain rate ($\dot{\epsilon}$) is calculated from the relation $\frac{v}{h_0}$, in which v is the instantaneous cross-head speed (maintained as constant in a UTM-based test) and h_0 is the

original height of a foam specimen. In these compression tests, the specimens were compressed up to 70% of their original height (i.e. by 35 mm). Experimental engineering stress-strain behaviors of the foam for the three cross-head speeds or equivalently constant strain rates mentioned are shown in Figure 1.

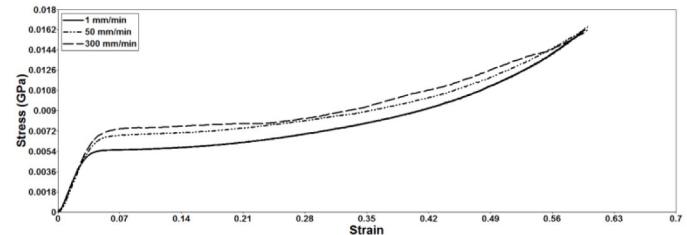


Figure 1. Stress-strain behaviors of foam at different constant cross-head speeds

IMPACT TESTS

A Versatile Test Rig consisting of a gravity accelerated and steel rod guided variable mass impactor, is used for impact testing of foam specimens. The test rig is shown in Figure 2. The impactor mass can be varied from 14 kg to 50 kg in steps of 5 kg, while impact velocity can be varied by changing the drop-height. Impact loads in the rig are captured using a 50 kN piezoelectric load cell, which is mounted on the impactor between its head and body through a high speed data acquisition system. The data acquisition system used for capturing the load-cell signals consists of a National Instruments make PCI-6220 data acquisition card installed in an Intel® Core™ i7 PC with Windows 7 operating system and a custom-coded LABVIEW-based user interface for operation and data gathering.



Figure 2. Impact testing machine with foam specimen placed on the base plate