Material Properties

The Deformation and Failure Response of Closed-Cell PMDI Foams Subjected to Dynamic Impact Loading

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Abstract

The present work aims to investigate the bulk deformation and failure response of closed-cell Polymeric Methylene Diphenyl Diisocyanate (PMDI) foams subjected to dynamic impact loading. First, foam specimens of different initial densities are examined and characterized in quasi-static loading conditions, where the deformation behavior of the samples is quantified in terms of the compressive elastic modulus and effective plastic Poisson's ratio. Then, the deformation response of the foam specimens subjected to direct impact loading is examined by taking into account the effects of material compressibility and inertia stresses developed during deformation, using high speed imaging in conjunction with 3D digital image correlation. The stress-strain response and the energy absorption as a function of strain rate and initial density are presented and the bulk failure mechanisms are discussed. It is observed that the initial density of the foam and the applied strain rates have a substantial influence on the strength, bulk failure mechanism and the energy dissipation characteristics of the foam specimens.

Keywords: Polymeric Foam; PMDI; Dynamic Loading; Digital Image Correlation; Shock Tube

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1. Introduction

Foam materials have recently gained attention in engineering applications, particularly in those where lightweight structural design and/or energy dissipation are essential design parameters [1].

Polymer foams are widely used in applications such as sandwich structures, automotive industries and packaging. Many of these applications inherently entail high loading rates, such as high speed vehicle accidents or impacts on packaged items. Due to unavailability of a well-defined material model at such a high loading rate, these structures are usually designed based on their quasi-static behavior. However, material properties obtained from quasi-static testing may not accurately characterize the material response in real situations at extremely high strain loading conditions, since the material response might be highly sensitive to the rate of deformation. There are also other material characteristics which elevate the level of complexity in precise evaluation of the material response of polymeric foams at high strain rate loading, namely the foam density and the cell structure [2-6]. At cellular scale, the deformation mechanism of foam materials include cell wall bending and stretching followed by post-yield wall buckling, while these microscale mechanisms contribute to the overall stiffness and strength of the material at larger scales. Thus, varying the cell structure and pore geometry in a foam specimen not only can change the material's bulk density, it will also substantially influence the stiffness, strength and bulk failure response of the material [1].

Researchers have been looking to understand the deformation behavior of foams at high strain loading conditions. So far, there have been both experimental and numerical studies to characterize the dynamic deformation and fracture behavior of foam structures considering

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4 various material parameters, such as the material cell structure and density [7-10]. However,
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7 owing to the high level of complexity encountered in the study of high strain rate deformation of
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9 these structures, a concise examination of the deformation response at elevated strain rates is
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11 very difficult to achieve. One of the more significant difficulties in the investigation of high
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13 strain rate deformation of foam structures arises from the low wave propagation speed in these
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15 materials [11]. During dynamic loading conditions, such low wave propagation speed results in
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17 difficulties achieving equilibrium state, particularly at the earlier stages of deformation [12-18].
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19 In such a condition, conventional measurement of load and deformation using only sensors
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21 located at the specimen ends can induce significant errors in the calculations. The problem
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23 becomes more pronounced in the presence of compressibility, the situation existing in the
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25 deformation study of polymeric foams [1].
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32 The effects of nonhomogeneous deformation and inertia present during dynamic deformation of
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34 materials have been a subject of study from early 1960's [19]. In the earlier works, great efforts
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36 were taken in order to include the influence of inertia into the measurements, accounting for the
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38 non-equilibrium state of deformation in high strain rate experiments. A survey within the
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40 literature of 1960's to 1990's indicates that researchers have attempted to consider the effect of
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42 inertia in their measurements by proposing simplified mathematical formulations, such as those
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44 documented by Samanta [20], Kukurema and Hutchings [21] and Gorham [22, 23]. However,
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46 more recently, with the advent of full-field measurement techniques such as digital image
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48 correlation (DIC) [24, 25], and the development of powerful high speed imaging devices, more
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50 accurate measurements of inertia forces and, consequently, a more realistic study of the
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52 deformation of specimens exposed to dynamic loading conditions has been facilitated [26].
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The main objective of the preset work is to study the constitutive behavior of polymeric foams with different mass densities subjected to direct impact loading using full field deformation measurements and inverse method. Foam specimens of different initial densities are characterized under quasi-static and direct impact loading conditions and their deformation response as well as their bulk failure mechanisms is investigated by accounting for the effects of compressibility and inertia stress. A simple one-dimensional mathematical model was used which enabled the determination of instantaneous density of the material over the entire duration of the exposure to loading. The full-field displacement and strain distributions obtained within the field of interest were used to calculate the local acceleration, and hence the inertia stress. Finally, the local stress-strain response of the specimens and the apparent global failure mechanism of the specimens exposed to direct impact loading conditions were captured, while efforts were made to correlate the different deformation and failure mechanisms to the cell structure of the specimens. To the best of the authors' knowledge, no research has so far been conducted to take into account the concurrent influences of the material compressibility and inertia loading in the dynamic loading of polymeric foams with different cell structures. This could potentially open new ways for more accurate experimental-based understanding of the deformation response of porous structures.

2. Materials and Methods

2.1. Material and Specimen Geometry

Rigid closed-cell PMDI (Polymeric Methylene Diphenyl Diisocyanate) foams of 160 kg/m³, 320 kg/m³ and 640 kg/m³ nominal densities were subjected to quasi-static and dynamic loading conditions [9]. Nominal densities of the foam specimens were measured in-house by measuring

the mass and the volume of each specimen, and were confirmed to be within 97% agreement with the values reported by the manufacturer. The differences in the cell structure of the foam specimens were exemplified in the SEM images taken from each specimen. The pore structures are vastly different in both size and regularity, as shown in Fig. 1. Cubic specimens of $25.4 \times 25.4 \times 25.4 \text{ mm}^3$ to be utilized in quasi-static experiments were extracted from the original cylindrical billets with the use of a milling machine. Cylindrical specimens of 25.4 mm diameter and 25.4 mm height were also fashioned from the as-received billets for dynamic loading experiments. Note that all specimens were cut from the as-received billets along the same direction. To facilitate the use of digital image correlation, it is necessary to apply a high contrast random speckle pattern on the surface of the specimens. Accordingly, a thin layer of white paint was first manually applied on the specimen surface. Then a fine pattern of random black speckles was applied on top of the white paint using an airbrush, resulting in a well-defined contrast exhibited by the pattern. A typical cubic specimen with the speckle pattern applied on its surface is shown in Fig. 2.

2.2. Quasi-static Loading

Quasi-static experiments were performed on specimens using a 250 kN MTS load frame. Loading was applied monotonically under displacement control mode at a rate of $1.5 \text{ mm} \cdot \text{min}^{-1}$, corresponding to an average strain rate of 10^{-3} s^{-1} . During testing, images were captured at a rate 1 frame per second using a 5 megapixel stereo camera system equipped with 55 mm lenses. These images were acquired to facilitate the use of 3D DIC, and to enable the determination of the exact instant at which specimen failure takes place. The arrangement of the cameras, specimen and the load frame used in the quasi-static experiments is illustrated in Fig. 3. The

distance between the cameras and the specimen was about 525 mm, and the angle between the two cameras was 24.4° . Further details on the cameras system parameters are listed in Table 1.

2.3. Direct Impact Loading

A shock tube apparatus was used to apply direct impact loading to the specimens at different loading rates. A shock tube is basically a thick-walled tube, made entirely of 6061-T6 aluminum extruded tubes of 75 mm inside diameter and 125 mm outside diameter in this case, consisting of two sections, driver and driven sections, which are separated by a stretched polyester film. The section existing at the closed end opposite the specimen, referred to as *driver section*, is pressurized with helium gas. The pressurization continues until the separating polyester diaphragm ruptures. With the burst of this diaphragm, the pressurized trapped helium gas expands rapidly from the high pressure driver section into the atmospheric pressure zone, referred to as *driven section*. As the helium gas expands through the driven section, a shock wave is formed by the highly compressed gas. The velocity and magnitude of pressure wave can be manipulated by varying the number of polyester diaphragms used to separate driver and driven sections or by reducing the end of the driven section. A 1 meter long reducing segment was added as the last segment of the driven section, nearest to the specimen, in this work with a tapered inside wall, reducing the inside diameter of the tube from 75 mm to 50 mm. The pressure ratio in driver/driven section of the tube in this work achieved using 2 sheets of 0.18 mm thick polyester diaphragms (Mylar sheets) is 2000KPa/101KPa. The pressure profiles achieved using different number of polyester diaphragms and further details on the utilized shock tube can be found elsewhere [27, 28]. A schematic view of the shock tube can be seen in Fig. 4a.

Video 3

[Click here to download Supplementary material: PMDI_640.mp4](#)

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4 In this particular experiment, the specimen was subjected to direct impact loading utilizing a
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6 projectile. The projectile was placed inside the shock tube in the driven section. The projectile
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8 was machined from 7068 aluminum alloy as a cylinder, hollowed from one end (to reduce the
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10 mass). The dimensions of the projectile were 72 mm in length and 49 mm in diameter, to fit into
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12 the reducing section. The projectile was also speckled in order to enable the measurement of its
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14 velocity at incidence with the foam specimen.
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20 Specimen load data was measured using a custom made loading fixture incorporating three
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22 piezotronic load cells placed behind the specimen (See Fig. 4b). These three load cells were
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24 mounted on a specially fabricated fixture on which the specimen was affixed with the use of
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26 lithium grease serving also as lubricant. Use of three load cells facilitates examination of the load
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28 distribution and results in a higher level of accuracy during measurements. An oscilloscope was
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30 utilized to acquire data from the load cells, as well as to trigger data and image acquisition.
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34 Images were captured using a Photron SAX-2 high speed stereo camera system at a rate of
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36 1.8×10^5 frames per second. Similar to the quasi-static experiments, the acquired images were
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38 used as the input for digital image correlation analyses, explained in detail in the following
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40 section. The experimental setup including the shock tube and the stereovision camera
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42 arrangement system is shown in Fig. 5.
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47 ***2.4. Digital Image Correlation***

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51 Displacement and strain data were extracted from images captured during the loading process in
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53 both quasi-static and dynamic experiments. This data was acquired through the use of 3D digital
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55 image correlation, as mentioned earlier. Camera resolutions of $2448 \times 2048 \text{ pix}^2$ and 256×168
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57 pix^2 were used to capture the full-field specimen deformation response in quasi-static and
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dynamic loading conditions, respectively. Images were then exported to the commercial DIC software Vic-3D[®] for further quantitative analysis. System parameters obtained from calibration of the stereo camera arrangement for both quasi-static and dynamic loading conditions are detailed in Table 1. The analysis of the images in the software Vic-3D[®] was performed using subset and step sizes of 47 and 15 pixels for quasi-static loading conditions, respectively; while these parameters were selected to be 25 and 3 pixels, respectively, for the case of dynamic loading. Note that the resolutions of measurements in the current study were calculated as 20.4 pix/mm and 18.5 pix/mm for quasi-static and dynamic loading conditions, respectively.

3. Determination of the Dynamic Stress-Strain Response

In order to study the flow behavior of a material under uniaxial loading, the stress and strains are conventionally extracted from boundary measurements. In particular, the stress developed within the material is usually calculated based on the force measured at the specimen ends; while strain is also acquired using the displacement of the specimen ends [17]. Such method of analysis is valid as long as the deformation takes place homogeneously within the material. However, in the case of dynamic loading conditions, and particularly dynamic loading of low impedance materials, force equilibrium is belatedly achieved, resulting in substantial error in the calculation of stress-strain response, provided that merely the boundary measurements are performed [15, 17]. To overcome this limitation and improve the accuracy of the measurements, the stress-strain response of the foam specimens in this work is determined by accounting for the effect of inertia.

The stress on the specimen at any given time, t , and any location z along the length can be calculated as:

$$\sigma_1(z, t) = \frac{F_1(0, t)}{A(z, t)} + \int_{\xi=0}^{\xi=z} \rho(\xi, t) \frac{\partial^2 u_1}{\partial t^2}(\xi, t) d\xi \quad (1)$$

where $F_1(0, t)$ is the force at any time t , measured by the load cells located at the specimen end.

$A(z, t)$ denotes the cross sectional area of the specimen at time t and position z . Note that the subscript “1” denotes the axial direction in this work. The second part in the right side of Eq. (1) represents the inertia term and can be calculated from the instantaneous acceleration and density at any given point in space and time. Due to the fact that polymeric foam specimens examined in this work are considered to be compressible solids, the effects of material compressibility and change of mass density during deformation needs to be taken into account. A simple mathematical model is used to calculate the material’s instantaneous density as a function of its initial density, and the measured full-field strain components. The model was proposed based on the principle of mass conservation and assuming that the density only varies along the axial direction. The derivation and formulation of the model is out of the scope of this work, and thus only the final mathematical formula is given as [29]:

$$\rho(z, t) = \rho_0 (\exp(\varepsilon_1(z, t)))^{2\nu(z, t)-1} \quad (2)$$

Here, ρ_0 and ε_1 are the initial density and the local axial strain component, and ν is the local effective plastic Poisson’s ratio at position z and time t . Similar mathematical expressions to determine the variation of density with deformation in polymeric foams are currently available in the literature [30]. However, the basic assumption in existing mathematical models is that no significant lateral expansion occurs during plastic deformation, i.e. assume zero Poisson’s ratio. However, the full-field measurements performed in the present work, as discussed in detail in the following sections, indicated that the foam specimens examined exhibit a noticeable lateral

expansion when exposed to both quasi-static and dynamic loading conditions. Accordingly, a modified mathematical expression given by Eq. 2, was proposed in the present work which enables to calculate the density at any given loading stage by taking the magnitude of local plastic Poisson's ratio into account.

The significance of such a simple mathematical expression is that the variables ε_1 and ν can be obtained from the experimental observations throughout the entire duration of the test, as discussed in detail in the following sections. The local Poisson's ratio in a cylindrical specimen can be calculated as the ratio of the local radial strain component to the axial strain, as given in Eq. (3):

$$\nu(z,t) = -\frac{\varepsilon_r(z,t)}{\varepsilon_z(z,t)} \quad (3)$$

For cubic specimens:

$$\nu(z,t) = -\frac{\varepsilon_x(z,t)}{\varepsilon_z(z,t)} = -\frac{\varepsilon_y(z,t)}{\varepsilon_z(z,t)} \quad (4)$$

where x , y and z represent the normal directions of a cubic specimen, compressed along the z -direction, within a Cartesian coordinate system.

Note that setting the value of ν as 0.5 results in a change in density equal to zero, i.e. the condition considered to be the general case in plastic deformation of incompressible solids, e.g. metals.

By introducing the instantaneous density equation, the final stress equation can be expressed as:

$$\sigma_1(z,t) = \frac{F_1(0,t)}{A(z,t)} + \int_{\xi=0}^{\xi=z} [\rho_0 (\exp[\varepsilon_1(\xi,t)])^{2\nu-1}] \frac{\partial^2 u_1}{\partial t^2}(\xi,t) d\xi \quad (5)$$

4. Results and Discussion

4.1. Quasi-Static Deformation and Failure Response

The quasi-static stress-strain curves obtained for specimens of different nominal densities are shown in Fig. 6a. In all cases, a linear stress-strain response is observed in the initial deformation stage, corresponding to linear elastic behavior of the specimens at lower compressive loads. The effective compressive elastic moduli, E , were also obtained by fitting the best line to the stress-strain curves prior to the elastic limits. The effective elastic moduli measured in this work show a significant sensitivity to the specimen density, as shown in Fig. 6b.

The elastic deformation is followed by a constant decrease in the stiffness to reach a plateau. Such plateau are common in foam specimens and correspond to the high energy absorption characteristics of these materials under quasi-static loading conditions [1, 31, 32]. A final densification stage in the quasi-static stress-strain response of all specimens occurs, being most prominent for the case of 320 kg/m³ specimen after 30% strain. At this stage, the stress levels in the 320 kg/m³ specimen slightly rises from its plateau at 7 MPa to 11.5 MPa at failure after the densification stage.

Different quasi-static mechanical responses observed for specimens with different nominal densities can be explained through the differences between their cell structures. As documented by Gibson and Ashby [1] and Mills and Zhu [7], the failure in closed cell foams takes place as the axially compressed cell walls undergo buckling. As observed in the SEM images of the specimens in this work (Fig. 1), the size of cell walls changes remarkably with density such that,

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4 for instance, a significantly larger amount of solid structure constitutes the cell structure of the
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6 640 kg/m³ specimen, compared to significantly thinner cell walls in the 160 kg/m³ specimen.

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9 Such thin sections present within the material's cell structure make it more susceptible to micro-
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11 buckling in these regions, noticeably lowering the compressive strength of the material.
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15 Failure was observed to take place at multiple shear planes within the specimens with 320 kg/m³
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17 and 640 kg/m³ initial densities, as shown in Fig. 7. The shear band failure mechanism observed
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19 for these specimens is very similar to those observed in case of solid non-porous structures. The
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21 evolution of shear strain on the surface of the 640 kg/m³ density specimen, shown in Fig. 8,
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23 supports the above statement. For the specimen with lowest density, on the other hand, no shear
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25 band formation was observed. The failure of this specimen occurred followed by crushing of the
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27 specimen, with no significant shear strain.
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33 Finally, the effective plastic Poisson's ratio, ν , the instantaneous density and the energy
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35 dissipation during deformation of the specimens in quasi-static conditions are determined.
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38 Typical variation of the transverse strain component and the specimen density vs. axial strain is
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40 shown in Fig. 9 for the specimen with initial density of 320 kg/m³. Note that, due to the
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42 homogeneous distribution of strain in quasi-static loading conditions, the local and global
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44 average Poisson's ratios in each case were calculated to obtain very similar values. Therefore, in
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46 the quasi-static loading conditions, only a single value for the effective plastic Poisson's ratio,
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48 i.e. average value of the parameter over the entire region of interest, was reported for each
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50 specimen.
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55 Based on the stress-strain curves obtained from quasi-static tests and the instantaneous change of
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57 density calculated for different specimens, the strain energy absorbed during the quasi-static
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4 deformation was calculated [6] The effective plastic Poisson's ratio and the absorbed energy
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7 calculated for different specimens under quasi-static loading conditions are listed in Table 2. .
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10 **4.2. Dynamic Deformation Response**

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13 The variation of axial strain component averaged over the entire region of interest for each
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15 specimen subjected to dynamic impact loading is plotted against the time span of the
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17 deformation, as shown in Fig 10. The slope of the best linear fit to each curve was then taken as
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19 the average strain rate, as shown in Fig. 10. The obtained strain rates are consistent for the two
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21 denser specimens, with strain rates approaching 2500 s^{-1} in these two cases. The strain rate
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23 calculated for the lowest density specimen is approximately half of those calculated for the other
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25 specimens, which indicates a very different material response for this specimen when subjected
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27 to dynamic impact loading with a similar projectile velocity (about 75 m.s^{-1} ($\pm 5\%$)). Such
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29 behavior was also noted in the bulk failure mechanism of the lowest density specimen subjected
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31 to dynamic loading, which is described in detail later.
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38 An interesting point in the analysis of dynamic deformation response of these specimens is that
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40 the axial strain would not be uniformly distributed along the axis of the specimens exposed to
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42 dynamic loading conditions. For instance, consider Fig. 11 where typical evolution of the axial
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44 strain at three different locations along the axis of the specimen with 640 kg/m^3 initial density
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46 has been plotted. The time shift between each two points of interest is substantial, as seen in this
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48 figure. It is evident from this figure that the specimens are actually in a transient state during the
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50 impact loading conditions, which also takes place in actual events of blast and/or crash. It was
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52 found that, depending on the specimen density, 15-30 μs is required for the wave to propagate
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4 through the specimen, which is in good agreement with the wave velocity estimated from the
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6 elastic modulus and the initial density of the specimens [17].
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10 To calculate the change of density during the dynamic deformation conditions from Eq. (2, using
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12 the local strain data obtained from DIC analyses, the local plastic Poisson's ratio in each case
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14 was determined. Typical curves showing the evolution of local plastic Poisson's ratio and,
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16 accordingly, the local density of the specimen with 640 kg/m^3 initial density are depicted in Fig.
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20 12. To compare the effective plastic Poisson's ratios during dynamic deformation of the foam
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22 specimens, the global plastic Poisson's ratios were also determined for each specimen by
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24 averaging the local evolution of Poisson's ratio over the entire region of interest. The effective
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26 plastic Poisson's ratios calculated for the specimens are listed in Table 3. The average Poisson's
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28 ratios determined in the dynamic loading condition are also within 10% difference of their quasi-
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30 static counterparts. This indicates the rather insignificant influence of the deformation rate on the
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32 relative lateral expansion of the foam specimens examined in this work.
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37 The dynamic stress-strain curves, including the inertia effect obtained at three locations across
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39 the specimen length (one near the load cell side, $Z=0$, one near the projectile side, $Z=1$, and one
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41 in the middle, $Z=0.5$, See Fig. 11), and their corresponding average of all the three different
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43 foams, are depicted in Fig. 13. Non-uniform distribution of stress and strains across the axis of
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45 each specimen observed in each case is attributed to the significant influence of the inertia loads
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47 developed [17]. Also, the level of heterogeneity of the stress was found to be higher during the
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49 earlier stages of deformation. This observation is in agreement with previously published results,
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51 and is inferred to be due to the effect of dynamic non-equilibrium at the earlier moments of
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53 deformation [15, 17, 26].
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The comparison of the average stress-strain curves for specimens of different initial densities are plotted in Fig. 14. Remarkably different behavior is observed between specimens of different densities subjected to impact loading conditions. To make a quantitative comparison between the strength of the foam specimens subjected to quasi-static and dynamic loading conditions, the achieved peak stress values are listed for different specimens in Table 4. An increase in the maximum stress values are observed comparing the maximum stress levels achieved in quasi-static and dynamic loading conditions. This indicates a stronger, yet more brittle material response at higher strain rates. The strain energy absorbed during the deformation of the foam specimens in dynamic loading conditions were also calculated using an approach similar to that used for quasi-static loading, by integrating the area under the stress-strain curve. The calculated values are listed in Table 5. Comparing the data shown in Table 5 with those listed earlier in Table 2, it is indicated that the decrease in the magnitude of the absorbed strain energy is most prominent for the lowest density specimen (89% decrease in the absorbed energy). On the other hand, the foam specimens with 320 kg/m^3 and 640 kg/m^3 initial density exhibit substantially lower decrease in the strain energy absorbed in dynamic loading conditions ($\sim 43\%$ decrease in the magnitude of the absorbed strain energy).

4.3. Dynamic Local and Bulk Failure Modes

The bulk failure behavior of the two denser specimens, i.e. specimens with 320 kg/m^3 and 640 kg/m^3 initial densities, was characterized as being associated with the formation of multiple shear planes within the specimen, as shown in Fig. 15. The shear planes in highest density specimen form at more locations across the specimen axis, indicating that kink band formation is the primary failure mode. On the other hand, for the case of the lowest density specimen, no significant shear deformation and failure was observed. The dynamic failure of this specimen

was observed with the specimen being crushed, indicating that elastic/plastic buckling is the primary failure mode. This observation indicates that as the density of the foam increases, the failure mode changes from elastic/plastic buckling to kink band formation.

The microstructural studies of cellular materials in the literature also supports the observation made in the current study. For instance, the study by Vural and Ravichandran [32] reveals that failure mode transition in cellular materials subjected to compression loading, from elastic/plastic buckling to kink band formation, occurs as the density increases. For the case of the lowest density specimen examined in this work, its bulk failure response is governed by buckling due to the very thin cell walls of the material's cellular structure. The thin cell walls are not able to sustain a large impulse type load and collapse due to elastic/plastic buckling without any significant resistance to the exerted load. On the other hand, the two denser specimens, with relatively thicker walls, can tolerate substantially larger applied loads without buckling, and later failed by kink band formation. The shear band formation in the two high density foam materials is illustrated in Fig. 15. Videos of the deformation and failure of the specimens exposed to dynamic impact loading are available as supplementary material.

5. Conclusions

Deformation and bulk failure mechanisms of closed-cell PMDI foams with different initial densities were studied using high speed photography in conjunction with 3D digital image correlation. The effects of change of material density as well as the inertia stresses developed during high strain rate loading of the specimens were included in the analysis, using the full-field measurements facilitated by DIC. The foam specimens exhibited substantial strain rate sensitivity in terms of compressibility, stress-strain behavior and failure response. The effect of

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4 inertia stresses were shown to be remarkable in the examined materials, due to their low
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6 impedance properties. The inertia effect was also demonstrated to be more pronounced for the
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8 case of lower density (with lower elastic modulus) specimen. The bulk failure mechanism of the
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10 specimen with lowest initial density was also indicated to be significantly different from the
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12 other specimens, both in quasi-static and dynamic loading conditions. The differences observed
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14 in deformation and failure response of the foams examined in this work were explained through
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16 the different pore structures of the specimens.
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36 **Supplementary Material**

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39 Video 1: The deformation and failure of the foam specimen with 160 kg/m^3 initial density
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41 subjected to direct impact loading. (file name: PMDI_160.mp4)
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45 Video 2: The deformation and failure of the foam specimen with 320 kg/m^3 initial density
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47 subjected to direct impact loading. (file name: PMDI_320.mp4)
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51 Video 3: The deformation and failure of the foam specimen with 640 kg/m^3 initial density
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53 subjected to direct impact loading. (file name: PMDI_640.mp4)
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Figure Captions

Fig. 1- Scanning electron microscope images of the foam specimen with nominal densities of (a) 160 kg/m³, (b) 320 kg/m³ and (c) 640 kg/m³.

Fig. 2- (a) Typical speckled cubic specimen, with the grey scale histogram of the speckle pattern shown in (b).

Fig. 3- (a) the experimental setup used to test the foam specimens in quasi-static loading conditions, with a higher magnification image of the cubic specimen between the machine platens in (b).

Fig. 4- Schematic view of (a) shock tube and (b) the loading fixture.

Fig. 5- The experimental setup used to apply dynamic impact loading on the specimens.

Fig. 6- (a) The stress-strain curves obtained from quasi-static loading of the specimens, with a high magnification of the initial elastic region shown in (b).

Fig. 7- The initial and failed specimens with (a) 160 kg/m³, (b) 320 kg/m³ and (c) 640 kg/m³ initial densities, under quasi-static loading conditions. Regions on which failure was first observed have been marked.

Fig. 8- Evolution of shear strain on the surface of the specimen with 640 kg/m³ initial density. The corresponding axial strain at which each image was taken has been written on the top left corner.

Fig. 9- Variation of transverse strain and normalized density with respect to the applied axial strain for the specimen with initial density of 320 kg/m³.

Fig. 10- The evolution of strain with time for specimens of different initial densities, subjected to impact loading conditions. The average strain rate was calculated for each case as the slope of the best fitted line.

Fig. 11- (a) The non-uniform distribution of the axial strain along the specimen length, with the axial strain history curves of the points of interest in (b). Z represents the normalized distance along the axis of the specimen subjected to dynamic loading.

Fig. 12- Variation of (a) local Poisson's ratio and (b) local normalized density for the specimen with initial density of 640 kg/m^3 . Z represents the normalized distance along the axis of the specimen subjected to dynamic loading (See Fig. 11).

Fig. 13- The stress-strain curves calculated at different locations across the specimen axis for specimens with (a) 160 kg/m^3 , (b) 320 kg/m^3 and (c) 640 kg/m^3 initial density.

Fig. 14- Dynamic stress-strain curves determined for specimens of different initial density.

Fig. 15- The bulk failure mechanism of specimens subjected to shock loading for specimens with (a) 160 kg/m^3 , (b) 320 kg/m^3 and (c) 640 kg/m^3 initial densities. The development of shear planes within the two denser specimens was observed and are marked with dotted lines.

Tables

Table 1- System parameters obtained from calibration of the stereo camera arrangements used in the quasi-static and dynamic loading conditions

Parameter		Quasi-static Testing		Dynamic Testing	
		Camera 1	Camera 2	Camera 1	Camera 2
Center - x	(pixels)	1202	1221	-190	-178
Center - y	(pixels)	919	1027	-176	-185
Focal length - x	(pixels)	17706	17758	5366	5384
Focal length - y	(pixels)	17705	17761	5368	5385
Skew (°)		-0.99	-1.23	0.097	0.026

Alpha (°)		-0.345		13.872	
Beta (°)		24.402		-1.186	
Gamma (°)		-0.149		-1.084	
Tx (mm)		-238.61		21.32	
Ty (mm)		-0.56		253.38	
Tz (mm)		60.28		-1.05	

Table 2- Effective plastic Poisson's ratio, ν , and the strain energy calculated for the specimens of different initial densities subjected to quasi-static loading conditions

Initial Density (kg/m³)	Effective Plastic Poisson's Ratio	Strain Energy (J)
160	0.362	20.1
320	0.284	43.6
640	0.377	88.1

Table 3- Effective plastic Poisson's ratio, ν , calculated for the specimens of different initial densities subjected to dynamic loading conditions

Initial Density (kg/m³)	Effective Plastic Poisson's ratio
160	0.387
320	0.311
640	0.340

Figures

Fig. 1- Scanning electron microscope images of the foam specimen with nominal densities of (a) 160 kg/m³, (b) 320 kg/m³ and (c) 640 kg/m³.

Fig. 2- (a) Typical speckled cubic specimen, with the grey scale histogram of the speckle pattern shown in (b).

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Fig. 14- Dynamic stress-strain curves determined for specimens of different initial density.

Fig. 15- Variation of peak stress with the initial density for the foam specimens subjected to quasi-static and dynamic loading conditions.

Fig. 16- The strain energy absorbed during the deformation of foam specimens with different initial densities, subjected to quasi-static and dynamic loading conditions.

Fig. 17- The bulk failure mechanism of specimens subjected to shock loading for specimens with (a) 160 kg/m^3 , (b) 320 kg/m^3 and (c) 640 kg/m^3 initial densities. The development of shear planes within the three denser specimens was observed and are marked with dotted lines.