Chapter 41
Energy Absorption Characteristics of Graded Foams Subjected to High Velocity Loading

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Abstract In this study the effect of layer stacking arrangement on the energy absorption characteristics of density-graded cellular polymers subjected to high velocity impact is investigated experimentally. Dynamic loading is performed using Split Hopkinson Pressure Bar (SHPB) which is also modified for a direct impact experiment. Different bulk density polymeric foam layers are bonded together in different stacking arrangements and subjected to impact loading. Ultra-high speed imaging is implemented to measure the deformation and observe the formation and propagation of compaction waves during direct impact. The effect of the orientation of the discrete layers on the dynamic stress-strain response is analyzed using digital image correlation (DIC). The effects of material compressibility are implemented to the analysis. The approach uses DIC to calculate the full-field acceleration and material density, later used to determine the stress gradients developed in the material. The best arrangement of layer structure is chosen by the highest energy absorption characteristics measured. Failure mechanisms associated with energy dissipation in graded materials are discussed.

Keywords Dynamic loading · Polymeric foam · Digital image correlation · Energy absorption · Graded materials

41.1 Introduction

Polymeric foams are cellular materials that in many industries such as aerospace, automotive, and military have become of great deal of interest. These cellular structures are ultra-light solids which absorb substantial energy in compression. Its many applications include absorbing impact and shock mitigation through energy dissipation by progressive local crushing. It is well known that energy absorption is strongly related to the foam density. Functionally Graded Materials (FGM) are advanced engineering materials that enable a material to have the best properties of multiples materials. The concept of Functionally Graded Foam Material (FGFM) has been introduced to improve upon certain properties as compared to a homogenous foam. The significant advantage of functionally graded foam materials is the optimization of strength to weight ratio. It is well established that higher density results in higher strength. Graded foam has the appeal of higher strength (higher density) combined with lighter weight (lower densities). The advent of graded foam has mostly been analyzed through simulations and analytical works. Many researchers have experimentally investigated the dynamic response of homogeneous foams, as well as there has been some theoretical and numerical work done on density-graded cellular materials. Ciu [1] tested the variation of gradation of the foam characteristics with finite element simulations and found improved performance over single-phase foams. Kiernan [2] developed a finite element model of the SHPB to study the wave propagation through FGFM's. The impact response of density graded cellular polymers has been analyzed by observing the propagation of compaction waves using DIC [3].

The objective of this present study is to experimentally analyze the energy absorption and strength properties of FGFM's subjected to high velocity loadings. The stacking sequence of discretized layers of different bulk densities is varied to determine the ideal gradation for load bearing performance. FGFM samples are constructed and subjected to dynamic loading via SHPB to generate stress in the discretized foam samples. Based on the experimental results the effects of orientation on the response of FGM's is analyzed by observing the stress-strain response. The yield point of the tests was calculated to determine which of the four different stacking arrangements was stronger. To demonstrate the SHPB results are admissible, DIC is utilized to characterize the full field deformation.

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41.2 Materials and Methods

The polyurethane foam was purchased from General Plastics, specifically the FR-6700 Aerospace grade series. This rigid, closed-cell foam is ideal because of its high strength-to-weight ratio. The five polymeric foams used to fabricate the layered specimens had densities of 160, 240, 290, 320, and 400 kg/m^3. Each layer was machined to 17 × 17 × 5 mm^3 and then polished using silicon carbide papers to have a smooth surface, suitable for speckling. The layers were bonded together with a thin layer of highly-flexible polyurethane adhesive. It is vital that the adhesive is flexible to account for small relative lateral deformation of the layers and to minimize shear stress developed within the interface. The final length of the specimens is 25 mm. The different sequences studied took on either a stepwise or sandwich configuration as the following stacking arrangements: 160/240/290/320/400, 400/320/290/240/160/, 160/290/400/290/160, and 400/290/160/290/400. A schematic and picture of one of the stacking sequences is shown in Fig. 41.1.

Table 41.1 reports the manufacturer mechanical properties given. Before speckling, a marker was used to draw a line between the layers to indicate the interfaces. A small piece of tape was used to cover a narrow strip of the front surface before speckling to help distinguish the different layers during deformation. The front surface of the specimens was painted white and then black speckling was applied using conventional spray painting method. A schematic of the experimental setup is shown in Fig. 41.2.

The elements of the operation include a dynamic loading device, bar components, data acquisition and recording device, and high speed imaging system. The sample was loaded dynamically using a SHPB. Polycarbonate bars were used because testing low impedance materials such as foams requires low impedance bars to ensure a clear transmission wave is recorded and is easily discernible from any noise. To measure the full-field deformation during loading a single ultra-high speed HPV-X2 camera (Shimadzu) was used. The camera is capable of acquiring 128 images at the full-field resolution, and for this particular work and imaging rate of 200,000 frames per second was utilized. The camera was equipped with a 100 mm macro lens (Tokina) providing an optical resolution of 100 μm/pixel. A flash monolight (Photogenic) was used to illuminate the area if interest on the sample after trigger from the strain gages.

41.3 Results and Discussion

The results presented are just from the preliminary tests and much of this work is still ongoing. The stepwise increasing density and stepwise decreasing density results are shown in this current study. The primary means by which a foam absorbs energy is by plastic deformation [4]. The deformation response is analyzed using the digital image correlation code, VIC-2D. Figures 41.3 and 41.4 shows the contour plots of the axial strain in the two converse specimens during the collapse of the

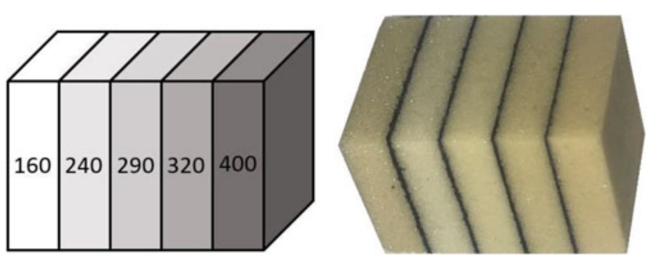

Fig. 41.1 Specimen stacking arrangement schematic and photograph

Table 41.1 Manufacturer elastic modulus and compressive strength

Density (kg/m3)	Elastic modulus (MPa)	Compressive strength (MPa)
160	60.7	2.3
240	161.0	5.8
290	196.9	7.2
320	244.1	9.6
400	344.2	14.0

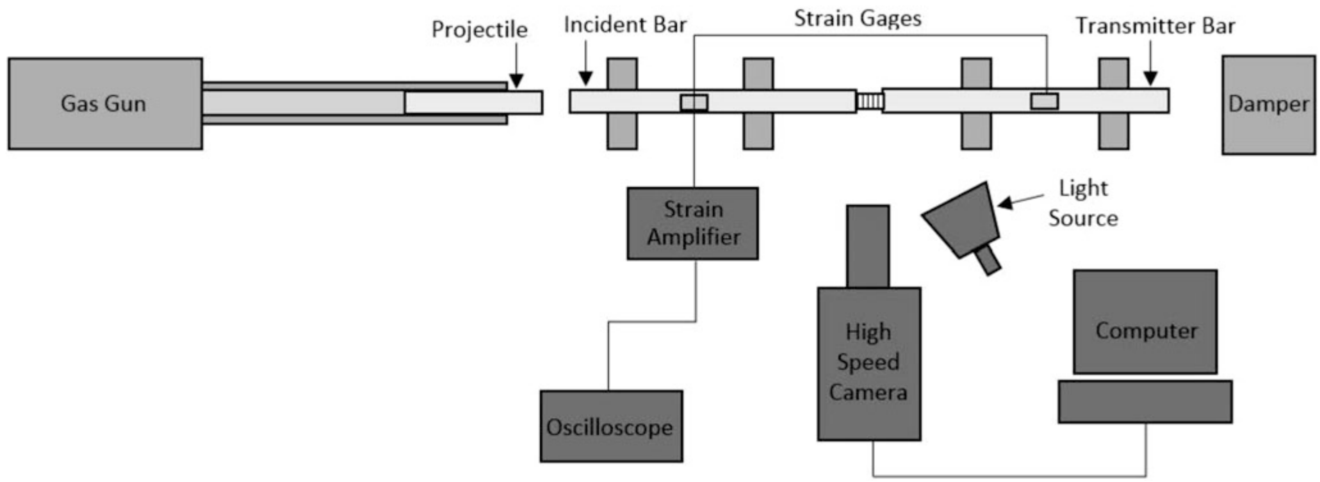

Fig. 41.2 Experimental setup schematic

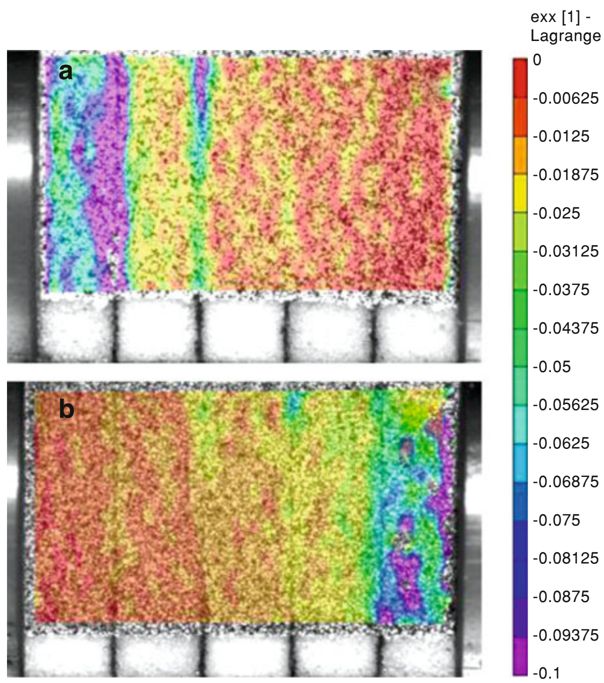

Fig. 41.3 Axial strain of (**a**) low to high density (**b**) high to low density

first layer. It is obvious that the first picture, the high-to-low density specimen, sees the highest strain at the far end of the sample, where the 160 kg/m^3 layer is. The low-to-high density specimen sees the highest strain at the impacted end, where the layer with the lowest compressive strength is located.

A point was extracted from the center of each layer during the post-processing using VIC-2D and the axial strain versus time is shown in the graphs below. It is apparent from the plots that the strain along the specimen is heterogeneous, varying spatially along the axis of the length. In both arrangements it can be observed that all the layers had begun to all be compressed together, but then the lowest density layer started to see much higher deformation. The failure progresses sequentially along the length of the specimen. The lowest density deforms plastically and then is fully densified (final failure of that layer) and then the strain propagates to the next lowest density layer. During the first incident wave only the two lowest density layers saw total failure. The two crushed layers started to compress the next lowest density layer, but the two high density layers still saw little effect. It was not possible to capture the final strain of the three highest density layers due to fragments of foam that were detached from the first two layers when they were being crushed. There does appear to be a slight variation in the time of failure of the different layers based on their orientation to the loading direction.

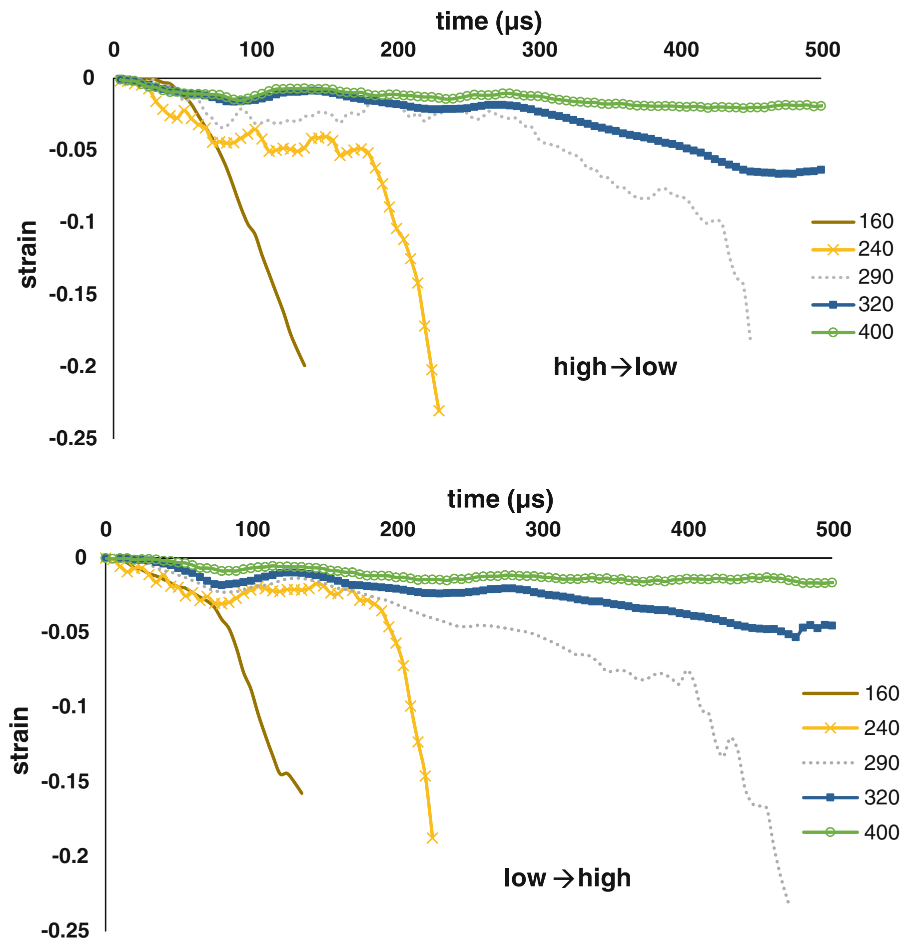

Fig. 41.4 Axial strain points from each layer

41.4 Summary

Functionally graded materials have the advantage of achieving tailored morphologies for desirable structural properties. The effects of stacking sequence on the energy dissipation of functionally graded foams under dynamic deformation was studied. The goal is to optimize the arrangement of layers of different bulk densities for superior energy absorption. High strain rate experiments were conducted on specimens that were made in-house and deformed using a standard SHPB. The compressive behavior was observed using a high speed camera and image correlation software. The full-field strain maps extracted from DIC were used to evaluate the mechanical response of the graded sample. By rearranging the configuration of the density gradation compared to the loading direction, a variation in the densification and strain progression occurs. These deformation characteristics will be used to tailor the material to a specific load and timeframe.

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