Chapter 4
Strain Localization Phenomena of Polyimide Aerogels Subjected to High Strain Rate Loading

Nathan Spulak, Benjamin Solomon, Charles Ruggeri, Sadeq Malakooti

Abstract Polyimide aerogel material specimens are subjected to compressive loading at quasi-static strain rates and at high strain rates on the order of 10^3 s^{-1}. The low-rate loading is performed using a hydraulic load frame, and the high-rate loading is performed using a specialized split-Hopkinson bar apparatus with a hollow transmitter bar for increased sensitivity of the transmitted wave measurements. Images are captured during each test and analysed with digital image correlation to determine the full-field strains across the specimen surface. The material specimens exhibit different strain localization behaviour at the different strain rates. Under low-rate loading the material deformation remains relatively uniform, while at high rates the material exhibits alternating regions of high and low compressive strain at repeated distances along the specimen length. This is potentially indicative of a more rapid, localized compaction and pore collapse phenomenon that occurs under high-rate loading.

Keywords polyimide aerogel · strain localization · hollow split-Hopkinson bar · digital image correlation · dynamic loading

Introduction

Polyimide aerogels have extremely low density, coupled with low thermal conductivity and high thermal stability up to temperatures of approximately 460°C. This makes them a material of interest for advanced impact protection systems for long-duration space missions – such as the use of polyimide aerogels as Whipple shield stuffing materials [1, 2, 3]. However, for accurate design of such structures, it is first necessary to experimentally determine the mechanical response of polyimide aerogels when subjected to dynamic loading. This is accomplished through the use of both quasi-static compression testing using a hydraulic load frame, coupled with high strain rate compression testing using a specialized split-Hopkinson bar (SHB) with a hollow transmitter bar for increased sensitivity of the force measurements. Digital image correlation (DIC) is used to measure the full-deformations on the specimen surface and calculate the resulting full-field strains.

Experimental Methods

The polyimide aerogels are synthesized using a sol-gel process, then isochorically frozen and sublimed under a dry gas flow [4]. This results in material specimens with an average density of 1.25×10^{-4} g/mm^3. The mechanical testing setups are

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shown in Figure 1. The quasi-static compression tests are performed on a hydraulic load frame located at the University of Alabama in Huntsville (UAH), using an actuator rate of 3.8×10^{-3} mm/s, and DIC images are taken with a pair of 2.3 Megapixel cameras operating at a frame rate of 0.5 fps. Specimens with diameter of 18 mm and length of 4 mm are used for the quasi-static testing.

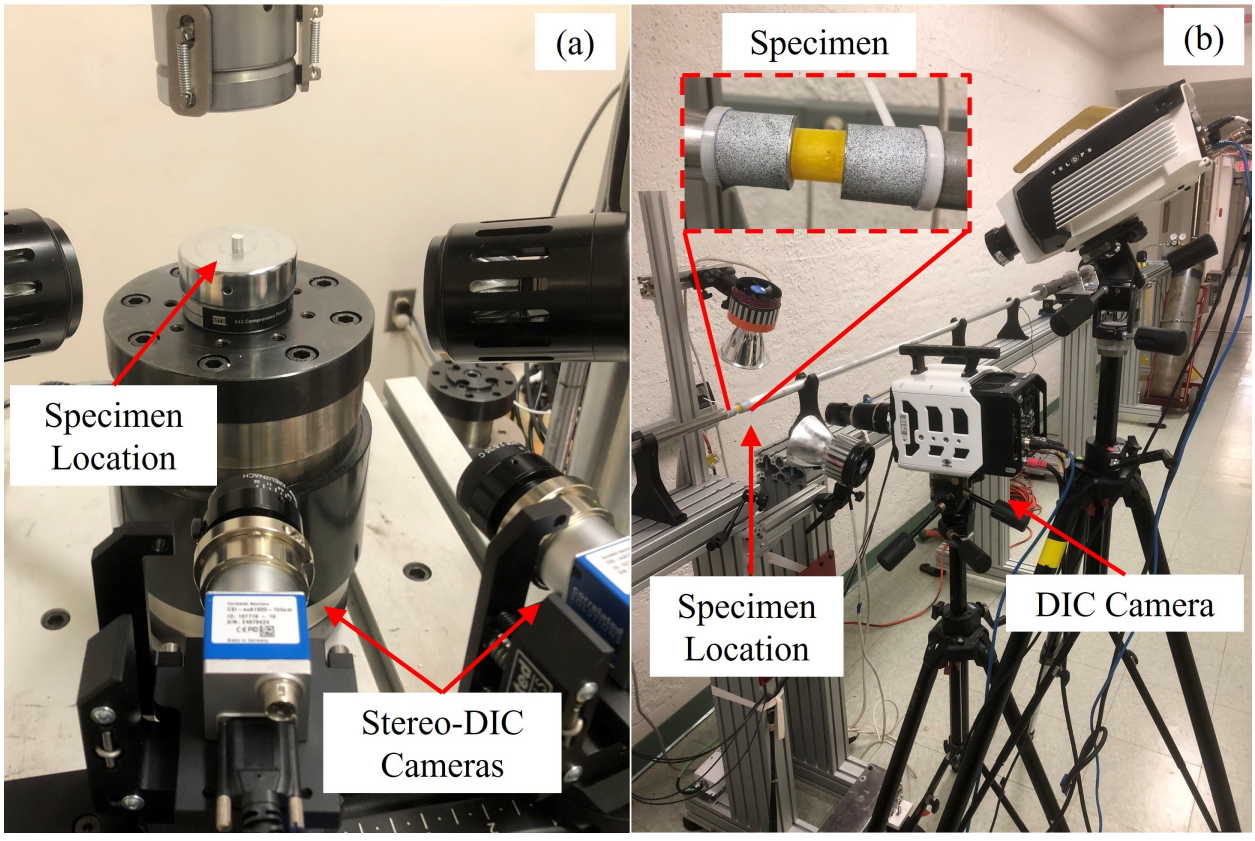

Fig. 1 (a) low-rate compression test setup on hydraulic load frame with stereo-DIC system, and (b) high-rate compression test setup using hollow transmitter bar SHB, with high-speed camera for DIC measurements.

The high-rate tests are performed using a specialized hollow SHB apparatus located at the NASA Glenn Research Center (GRC). A picture of the hollow SHB is shown in Figure 1(b), and a schematic is shown in Figure 2. A Phantom TMX 7510 high-speed camera is used to capture DIC images at a frame rate of 300,000 fps during the tests. The incident, transmitter, and striker bars are 7075 aluminum, with lengths of 1.8 m, 1.8 m, and 0.46 m, respectively. All bars have an outer diameter of 25.5 mm, and the striker and incident bars are solid cylinders. The transmitter bar, however, is hollow with inner diameter of 22.2 mm. Since the aerogel is a soft, low impedance material it is expected to have low transmitted forces during the SHB experiments, and therefore a hollow transmitter bar is used to increase the sensitivity of the transmitted wave measurements [5, 6]. Testing is performed at strain rates on the order of 10^3 s^{-1} on the aerogel specimens, and tests are performed on shorter specimens of length 4 mm by 18 mm in diameter to match the geometry of the low-rate tests, and on additional

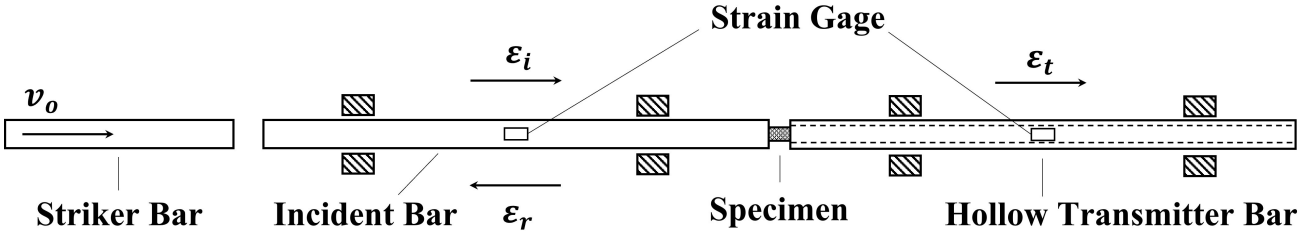

Fig. 2 Schematic of compression SHB apparatus with hollow transmitter bar.

longer specimens with 13 mm length by 18 mm diameter to better visualize the strain localization response along the gauge length.

For both quasi-static and dynamic tests, the specimen engineering strain (ε_{Eng}) is measured using a virtual DIC extensometer, and the local DIC Hencky strains along the axial centerline of the specimens are extracted.

Results

The axial compressive strains along the specimen gauge centerline are shown in Figure 3, at various timesteps as the tests progress (as denoted by the increasing values of the measured engineering extensometer strain, ε_{Eng}). It can be seen that at quasi-static loading rates, the polyimide aerogel material has a relatively uniform strain across the specimen length. However under dynamic loading, the deformation is no longer uniform but rather there are alternating regions of high vs. low compressive strain, in a repeating periodic pattern with distances of approximately 1.5 – 2 mm between the regions of highest strain concentration.

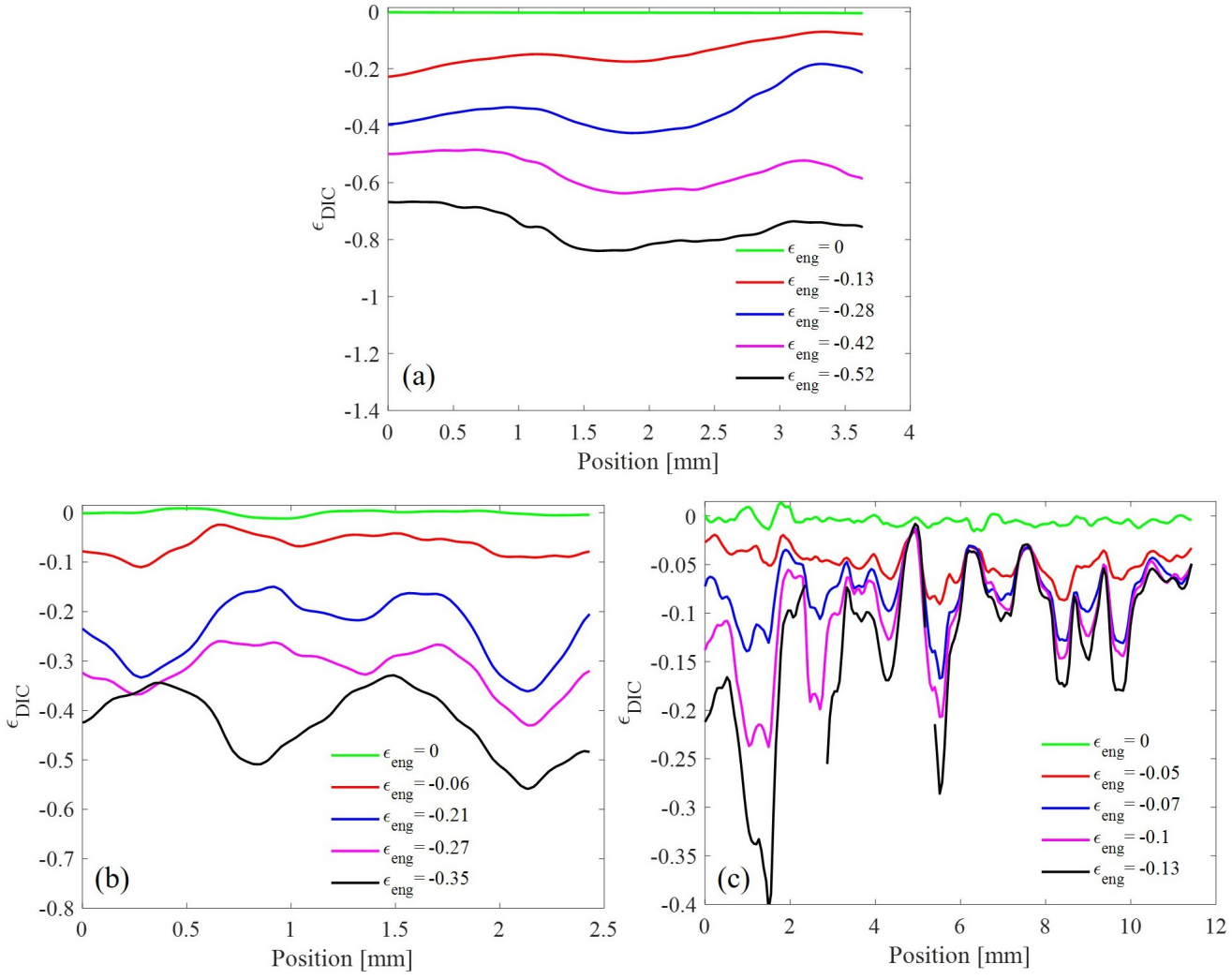

Fig. 3 Axial compressive strain along specimen centerline for a) quasi-static – 4 mm specimen length, b) dynamic SHB – 4 mm specimen length, and c) dynamic SHB – 13 mm specimen length.

Conclusion and Future Work

Polyimide aerogels exhibit different strain localization behavior when loaded at different strain rates. Under quasi-static loading the exhibit relatively uniform deformation, but at dynamic strain rates on the order of 10^3 s^{-1} the material displays a complex strain localization response with alternating pattern of high vs. low strain across its length as the test progresses. This strain localization is potentially indicative of a localized damage and pore collapse/compaction response that is more pronounced under dynamic loading. The fundamental phenomenon that drives this localization behavior will be assessed in future work using interrupted testing and microstructural analysis of the high strain regions. Additional future work includes assessing the differences in material strength and energy absorption at different strain rates, and also investigating the coupled thermo-mechanical response via the incorporation of infrared temperature measurements.

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