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1 Introduction

Low density polymeric foams are frequently used in a wide range of engineering applications due to their significant shock and vibration absorbing, sound insulating, and thermal insulating capabilities. One such example is the usage of polymeric foams as cushioning materials. In such an application, the polymeric foam material can be subjected to high strain rate impact, repetitive loading, large deformation, and complex stress states. To predict the response of polymeric foam materials under such diverse conditions would require detailed and accurate measurement of their mechanical properties. However, direct experimental observation and measurement of their behavior under such conditions is not trivial. As a result, the approach usually adopted is to conduct simple experiments, such as uniaxial compression. The experimental data are used to calibrate a constitutive model, and this constitutive model is then used to predict the behavior of the polymeric foam materials under other, more complicated loading conditions. Therefore, the ability to measure deformation in a polymeric foam specimen under complicated loading conditions becomes important and necessary because it will serve the following two purposes. First, it can be used to directly study the mechanical behavior of polymeric foams under these complicated loading conditions. Second, it can be used to compare against numerical simulations to validate the constitutive models.

In this investigation, we developed a simple experimental technique to measure the full-field and finite deformation in a polymeric foam specimen that is subjected to monotonic or cyclic tension, monotonic or cyclic simple shear, as well as their combinations.

2 Experimental Method

In this section, the experimental technique developed for the purpose of measuring full-field deformation in a polymeric foam specimen, and the procedure of preparing the test sample are described.

2.1 Dot-matrix deposition & mapping technique

In general, the deformation of a continuum object is a mapping relation between points of the same material particle before and after the deformation, i.e.,

\[ y = \hat{y}(x), \]

where \( x \) are the labels of material particles and \( y \) labels the point in space now occupied by the particle that is at \( x \) in the reference region. For a homogeneous deformation, \( \dot{y}(x) \) can be represented by

\[ \dot{y}(x) = Fx + b, \]

where \( b \) is a constant vector and \( F \) is a constant tensor. For any general deformation \( \dot{y}(x) \), one can show that it can be viewed as locally homogeneous. For homogeneous or locally homogeneous deformation, once the constant tensor \( F \) and the constant vector \( b \) are determined, the mapping relation between the point \( x \) in the reference configuration and the position of the same point in the current configuration \( y \), is totally determined. Meanwhile, by using left polar decomposition, i.e., \( F = VQ \), where \( Q \) is a proper orthogonal tensor and \( V \) is a symmetric and positive definite tensor also known as the left-stretch tensor, the Almen's strain tensor \( \epsilon \) can be calculated through

\[ \epsilon = \frac{1}{2}(I - F^{-T}F^{-1}) = \frac{1}{2}(I - V^{-2}), \]

where \( I \) is the second-order identity tensor. In this formulation, \( V \) and \( \epsilon \) are described in the current configuration, or are associated with the Eulerian frame. Note that in the above discussion, we do not restrict the deformation to be infinitesimal. All the descriptions are valid for finite deformation. In the present experimental investigation, we will determine the deformation gradient tensor \( F \) for a planar deformation, and the strain tensor \( \epsilon \) is then given by (3).

The technique we developed for the present investigation is called dot-matrix deposition & mapping. In principle, this technique is very similar to the image correlation method [1], but avoids ambiguity due to the reflectivity change of the specimen surface during the deformation process, and it is readily applicable to situations with very large deformations. The drawback of this technique is that the spatial resolution is not as high as for the image correlation method. However, since we treat the polymeric foam as a homogeneous material, the length scale over which the polymeric foam can be treated as such is quite large. Before the experiment, a pattern of dot matrix is deposited on the surface of the specimen and the pattern is photographed at different moments during deformation. The image at each moment is then processed to identify the exact location of the center of each dot. Based on the coordinates of each dot, an element mesh for the moments before and after deformation can be constructed. Geometrically, each element in the reference configuration can be described
as a polygon with vertices of \( P_i \) \((i = 1, 2, \cdots, N)\), where \( N \) is the total number of nodal points of the element. Assuming that each element is undergoing homogeneous deformation, then each element in the current configuration can also be described as a polygon with vertices of \( Q_i \) \((i = 1, 2, \cdots, N)\). The relationship between the vertices is governed by

\[
y_i = F x_i + b, \quad i = 1, 2, \cdots, N,
\]

where \( x_i \) and \( y_i \) are the coordinates of the \( i \)-th vertex before and after deformation, respectively. Through the image processing, we know the coordinates \( x_i \) and \( y_i \) of the nodes of each element. For \( N \geq 3 \), both tensor \( F \) and vector \( b \) can be obtained through a least-square fitting routine and the deformation state in this element is determined. Repeating the process for all the elements, the full-field deformation within the sample is thus obtained.

### 2.2 Material description & sample preparation

The polymeric foam used in this investigation was flexible polyurethane foam. It was provided by Dow Chemical Company, Freeport, Texas, in the form of closed-mold cushions with a size approximately 380 × 380 × 110 mm. The microstructure of the polymeric foam is shown in Figure 1, obtained by scanning electron microscopy. The cell walls were ruptured by repeated crushing of the foam, to create reticulated open-cell foam. Overall, the cells were equiaxed and a range of cell sizes was present with the largest cells being just under 1 mm in diameter. The foam density was approximately \(0.036\) g/cm\(^3\). Using a density of \(1.2\) g/cm\(^3\) for polyurethane [2], this gives a relative density of 0.03, indicating that the foam was 97% open space, with only 3% solid matter.

Specimens for testing were cut from the foam using a bandsaw equipped with a scalloped double-bevel blade. The foam was cooled with dry ice vapor to increase its rigidity during cutting. The polymeric foam specimens used in the present study all have the shape of a cube approximately 25 mm on each side. The orientation of the rise direction of the foam was preserved. All testing was conducted with loading parallel to the rise direction.

The procedure of depositing a dot-matrix pattern on to sample surface is described below. First, a flat teflon plate with thickness of 6.5 mm was coated with a very thin layer of vacuum grease. This layer of vacuum grease serves as a releasing agent later. A template made of thin brass sheet, which has a matrix of drilled holes, was put on the teflon plate. The diameter of the holes on the template is about 1 mm, and the distance between two holes is about 2.5 mm. A light coat of glossy epoxy black paint was then sprayed on the template. Such a black paint was chosen for its viscosity so that the paint will flow slowly into the holes but will not flow underneath the template. The paint was allowed to set for a while, but before it became completely dry, a second coat was sprayed. The process was repeated approximately 8 to 10 times, then the template was removed carefully. This leaves a matrix of black paint dots on the surface of the teflon plate. Each dot has a diameter of approximately 1 mm and the distance between dots was about 2.5 mm. After the paint dots were completely dry, a second thin brass template, which also has a matrix of holes drilled with the same distance between holes (2.5 mm) but with a larger hole diameter (~2 mm), was placed on the teflon plate. The matrix of holes on the second template was lined up with the matrix of paint dots on the surface of the teflon plate. A layer of 3M adhesive was sprayed on the second template and the adhesive was allowed to flow into the holes. Immediately after the adhesive was sprayed, the second template was carefully removed. The polymeric foam specimen was slowly placed on the teflon plate, and a light weight was placed on top of the sample. After the adhesive cured, the polymeric foam specimen was lifted off. A matrix of black dots was retained on the surface of the sample. The images of the dot matrix on the surface of the polymeric foam specimens can be seen in Figures 3 and 6.

### 3 Experimental Observations

To illustrate the application of the dot-matrix deposition & mapping technique discussed in the previous section on measuring full-field deformation in polymeric foam specimens, in this section, we present experimental results for two different loading situations, cyclic tension and cyclic simple shear.

#### 3.1 Cyclic tension of a polymeric foam specimen

In the cyclic tension experiment, two T-shape aluminum pieces were glued with Deucan 2-Ton Crystal Clear Epoxy to the top and the bottom faces of the polymeric foam specimen. The assembly was then clamped in a tension fixture and was mounted in a conventional INSTRON 1125 screw-driven load frame. The experiment was conducted at room temperature (~20°C) and at a constant displacement rate of 10 mm/min. The variation of the applied tensile force as a function of displacement is shown in Figure 2. The polymeric foam specimen was subjected to several loading cycles, and as shown in Figure 2, during each loading cycle the specimen was deformed further than for the previous cycle. The circular dots in the figure indicate the maximum deformation during each
0.5. 10. 15. 20. 25. 30. Displacement, $\Delta L/(\text{mm})$

![Cyclic Tension Test](image1.png)

Figure 2: Variation of applied tensile force as a function of displacement for the cyclic tension test.

During the loading process, images of the dot matrix pattern were recorded using a digital camera. In Figure 3, images of the dot matrix on the surface of the tensile specimen before and during deformation.

![Figure 3: Images of the dot matrix on the surface of the tensile specimen before and during deformation.](image2.png)

Since the boundary condition along the top and the bottom surfaces are such that displacement along the horizontal direction is restrained to be zero, a shear component of the strain field is also present. For a true uniaxial stress finite deformation, one can show that the stretch along the vertical direction corresponding to the deformation state shown in Figure 4 is $\lambda = 1.7868$. As a result, the component of the Almansi strain tensor along the vertical direction can be calculated to be $\varepsilon_{22} = 0.3434$. Compared with the distribution of the strain component $\varepsilon_{22}$ shown in Figure 4, one can see that the center portion of the polymeric foam specimen can indeed be treated as having undergone a uniaxial stress deformation.

### 3.2 Cyclic simple shear of a polymeric foam specimen

In another experiment, we studied the behavior of polymeric foam under cyclic simple shear. In this experiment, two aluminum blocks were glued to the right and the left surfaces of the polymeric foam sample. The assembly was clamped to a custom-designed loading fixture, which was then mounted in the INSTRON 1125 test machine. To avoid sample rotation during the shearing process, two polymeric foam samples were clamped in the fixture, one on each side of the loading axis, which was attached to the load cell. A constant displacement rate of 5 mm/min was used. The variation of the applied shearing force on each polymeric foam sample as a function of the shearing displacement is shown in Figure 5.

Another polymeric foam specimen was subjected to several loading cycles, and during each loading cycle the specimen was deformed further than for the previous one. The circular dots in Figure 5 indicate the maximum deformation during each loading cycle and the last dot indicates the moment at which one of the foam samples failed.

In Figure 6, images of the dot matrix on the surface of the shearing specimen are shown before deformation and the moment indicated in Figure 5 by the letter B. After the image processing and the mapping calculation, all three in-plane components of the strain field were obtained and they are presented as contour plots shown in Figure 7. Once again, it would be of interest to compare the strain field shown in Fig-

![Cyclic Shearing Test](image3.png)

Figure 5: Variation of applied shearing force on each polymeric foam sample as a function of the shearing displacement for the cyclic simple shear test.

![Figure 4: Contour plots of all three in-plane strain components of the polymeric foam specimen subjected to tension.](image4.png)

Figure 4: Contour plots of all three in-plane strain components of the polymeric foam specimen subjected to tension.
Figure 6: Images of the dot matrix on the surface of the shearing specimens before and during deformation.

Figure 7 with the calculation by assuming that the deformation is the idealized in-plane simple shear.

Consider the deformation of idealized in-plane simple shear, where the relationship between material points in the current and reference configurations, corresponding to the present test, is given by

\[ y_1 = x_1, \quad y_2 = x_2 + \delta(x_1), \quad y_3 = x_3, \] (5)

where \( \delta(x_1) \) is the amount of shearing displacement along the \( x_2 \)-direction and it is only a function of the coordinate \( x_1 \). The in-plane components of the Almensi strain tensor can, therefore, be calculated to be

\[ \varepsilon_{11} = -\frac{\gamma}{2}, \quad \varepsilon_{22} = 0, \quad \varepsilon_{12} = \frac{\gamma}{2}, \] (6)

where \( \gamma = \delta'(x_1) \). In general, \( \gamma \) is a function of coordinate \( x_1 \). However, if we assume that \( \gamma \) is indeed a constant, one can show that for the deformation state shown in Figure 6, the in-plane strain components are \( \varepsilon_{11} = -0.4472, \varepsilon_{22} = 0.0, \) and \( \varepsilon_{12} = \pm 0.4729 \), respectively. By comparing these values with those shown in Figure 7, one can easily see the effect of the traction-free boundary conditions along the top and the bottom surfaces of the sample and the effect of the fixed displacement conditions along the left and the right boundaries, where material particle rotation was also kept to be zero.

4 Concluding Remarks

In this investigation, a simple experimental technique, dot-matrix deposition & mapping, was developed to study the full-field deformation in a polymeric foam specimen. One of the advantages of using this technique is that it can be easily applied to situations where large deformations are involved. The spatial resolution of the current technique is not as high as the digital image correlation method and some other optical techniques. Nevertheless, because the largest cell diameter of the polyurethane foam studied in this investigation is about 1 mm, the smallest length scale over which the polymeric foam material can be treated as a homogeneous solid would be at least several millimeters. For the element size used in the present study in the range of \( 2.5 \times 2.5 \) mm\(^2 \), the dot-matrix deposition & mapping technique would provide enough detail about the behavior of polymeric foam materials under complicated deformation states and under complicated loading conditions. It will also provide useful information to compare with numerical simulations so that the constitutive models can be validated.

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References
