Keysight Technologies
Quasi-static and Dynamic Compression Behavior of Flexible Cellular Material

Application Note

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Introduction

Cellular solids are promising engineering materials because of their potential in offering simultaneous control over strength, stiffness and weight in a given application [1, 2]. Although cellular materials are ubiquitous in nature, their engineering applications have been limited until recent years. These materials are not only important as lightweight structural components but also as scaffolds for biomedical tissue engineering. Many of these applications require flexibility and high mechanical stability of the structure. Hence, it is important to characterize the mechanical properties of these cellular solids.

One popular man-made cellular material is flexible polyurethane foam. Polyurethanes are a family of heterogeneous polymers that contain the urethane linkage (carbamate group) within the polymer chains [3].

Different functional groups that can be incorporated into the polymer network have attributed to the wide range of properties and applications for polyurethane materials. Elastomeric polyurethanes have found applications in packaging, household furniture, cushioning for car-seats, and in biocompatible scaffolds for tissue engineering (Figure 1(a)) [4].

The deformation behavior of polyurethane foam under compression has been previously reported in literature [2, 5–8]. Different deformation mechanisms during compression have been identified using microscopic and x-ray microtomographic observations [6]. The compressive deformation of open-cell polyurethane foams exhibits three distinct regimes: a linear elastic regime due to elastic bending of cell walls, a plateau regime due to buckling of
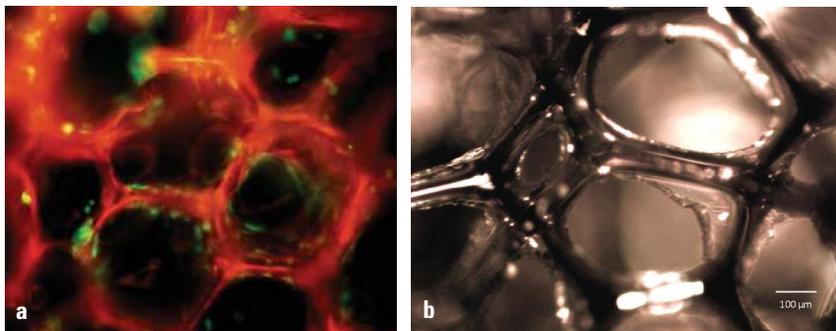
Figure 1. (a) Calcein AM staining of live cells (green) on a polyurethane scaffold, which autofluorescence red (Reference 4). (b) Open-cell polyurethane foam used in this study for compression experiments.

cell walls, and finally a densification regime. However, most of the reported literature has dealt with large samples of polyurethane foam. Despite the importance of mechanical properties of cellular materials for tissue engineering applications, there has not been a systematic study on the change of elastic property with increasing deformation in cellular materials.

In this study, the quasi-static and dynamic compression behavior of flexible open-cell polyurethane foam is investigated using the Keysight Technologies, Inc. UTM T150. It addresses the quasi-static and dynamic behavior of the foam specimen across all the different regimes of deformation. It also analyzes the strain-rate effect and the energy dissipation across different regimes of the deformation process. This application note demonstrates the importance of continuous dynamic mechanical characterization of flexible cellular materials. It becomes especially important for cellular materials with low stiffness and lack of availability in large volumes, such as materials for soft tissue scaffolds in biomedical applications.

Theory

Before discussing the results on flexible polyurethane foam, it is important to define the important parameters. The engineering stress in a compression experiment is defined as:

$$\sigma = \frac{F}{A_0} \quad (1)$$

where, F is the applied force and A_0 is the original cross-sectional area. The engineering strain is defined as:

$$\epsilon = \frac{\Delta l}{l_0} \quad (2)$$

where, Δl and l_0 are change in specimen height and the original specimen height, respectively.

The Young's modulus of the material is determined from the slope of the initial linear-elastic region of the engineering stress-strain curve.

In addition to the quasi-static stress-strain measurements, the continuous dynamic analysis (CDA) option on the UTM T150 also provides the capability to measure the modulus of the specimen dynamically over the complete range of strain. The CDA applies a force oscillation with amplitude of F_0, which causes a displacement oscillation of amplitude z_0. The displacement oscillation lags behind the force oscillation by a phase angle ϕ. The storage modulus of the specimen is related to the amplitudes and phase angle by [9]:

$$E' = \frac{l}{A}\left(\frac{F_0}{z_0}\cos\varphi\right) \quad (3)$$

Similarly, the loss modulus is:

$$E'' = \frac{l}{A}\left(\frac{F_0}{z_0}\sin\varphi\right) \quad (4)$$

where, l and A are the instantaneous height and cross-sectional area, respectively.

The dissipated energy per unit volume, W_d, is calculated from the area enclosed between the loading and unloading curves of the stress-strain plot.

Experimental Method

A piece of polyurethane foam, with length of 6.6 mm, breadth of 5.4 mm and height of 5.4 mm, was used for the compression experiments. The weight of the specimen was measured, with a precise balance, to be 0.0050 g. The density of the wall material of polyurethane foam has been previously reported to be 1200 kg/m^3 [2, 10], which gives a reasonable specific density of about 0.02 for our foam specimen. Figure 1(b) shows an optical picture of the open-cell polyurethane foam, which demonstrates the distribution of pore size and shape throughout the specimen.

The compression setup in the Keysight UTM T150 is shown in Figure 2. The 5 mm compression platens, available for the UTM T150, were fitted with thin
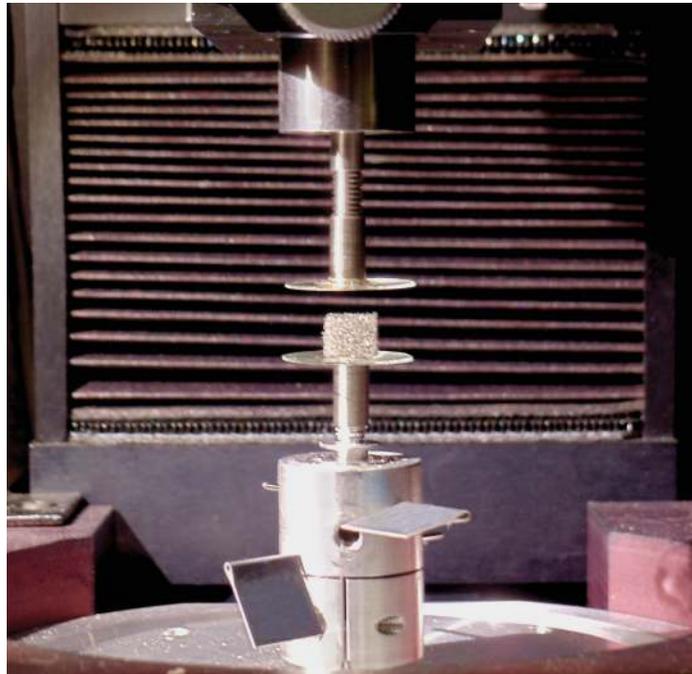

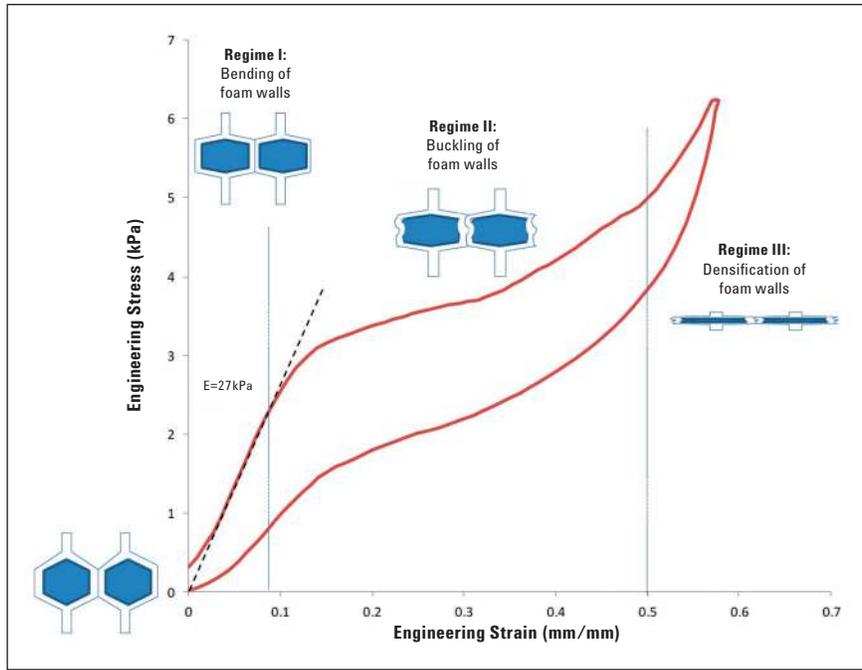Figure 2. Compression test setup for Keysight UTM T150.

Figure 3. Engineering stress-strain response from quasi-static compression test on flexible polyurethane foam. The schematics represent the deformation mechanisms at different stages of the deformation.

glass slides to increase the available surface area. It is important to note here that the compression platens should have proper alignment, which can be attained using the optional X-Y micropositioner available for the instrument. All the quasi-static and dynamic compression tests were performed with a strain rate of 3×10^{-3} s^{-1}, except the quasi-static measurements where the effect of strain rate was studied, where the specimen was characterized at three different strain rates of 5×10^{-3}, 5×10^{-2} and 1×10^{-1} s^{-1}. The continuous dynamic analysis during the compression test was performed using force amplitude of 4.5 mN at a frequency of 20 Hz.

To study the energy dissipation in flexible polyurethane foam during cyclic loading, the NanoSuite method has been designed for cyclic compression tests. The method can perform cyclic tests up to a constant maximum strain as well as cycles with increasing maximum strains for each cycle. The latter type of cyclic test was carried out during the present study.

Results and Discussion

A typical compressive stress-strain curve for flexible polyurethane foam, studied herein, is shown in Figure 3. Three distinct regimes, as reported previously, are clearly visible in the stress-strain response. The deformation mechanisms in different regimes are also represented by the simplified schematics in the insets of Figure 3. Regime I indicates the initial linear elastic region that represents the reversible elastic bending of the struts inclined at an angle to the loading axis [2]. The Young's modulus calculated from the slope of the stress-strain curve in Regime I is 27 ± 3 kPa. The empirical relationship, proposed in the literature, between the Young's modulus of the foam and its specific density is [2]:

$$\frac{E}{E_s} = C_2 \left(\frac{\rho}{\rho_s}\right)^2 \qquad (5)$$

where, E and E_s are the Young's moduli of the foam and the wall material, respectively. ρ and ρ_s are the densities of the foam and the wall material, respectively. C_2 is a constant with a value close to 1. The specific density for the foam specimen is about 0.02. Hence, by considering $E_s = 45$ MPa [11], the Young's modulus for the polyurethane foam is estimated to be 18 kPa. This is close to the value measured from the slope of the Regime 1 (Figure 3), and provides confidence in the measurements obtained from the Keysight UTM T150.

The plateau in Regime II is caused by elastic buckling of the foam walls parallel to the loading axis. It has been postulated that when a critical elastic buckling stress (deviation from linear elastic behavior) is reached, the buckling of foam walls percolates through the structure in the form of a deformation band, causing the plateau in Regime II. Hence, the width of the plateau in Regime II depends on the pore size and total height of the specimen.
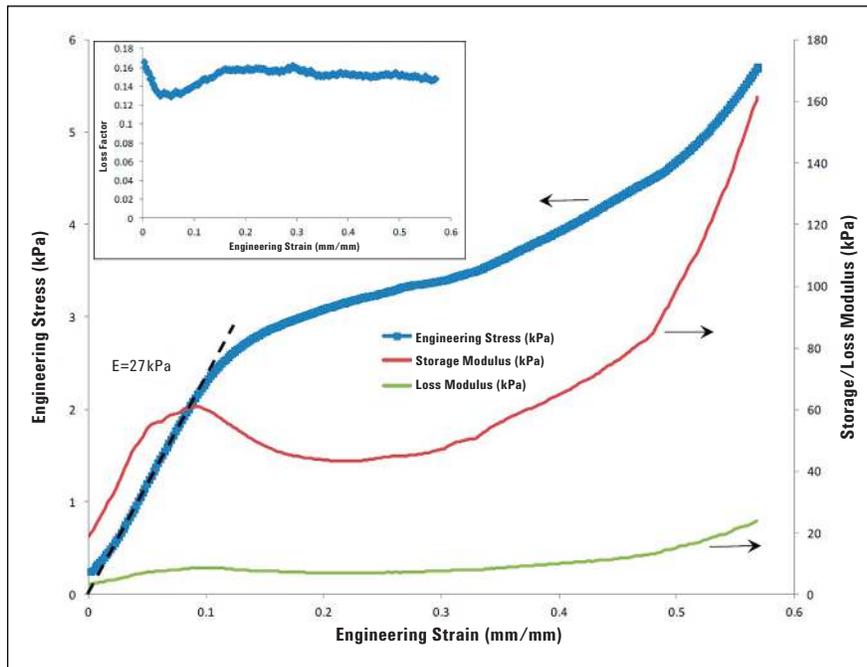
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Figure 4. Continuous dynamic analysis (CDA) showing change in engineering stress, storage modulus and loss modulus with increasing deformation of the foam specimen. The inset shows change in loss factor with strain.

Finally, in Regime III the foam walls densify and, if continued up to higher strains, should eventually reach the elastic response of solid polyurethane. Note that the boundary between Regimes II and III is not very well defined because of the random size and shape distribution of the polyurethane foam [6].

The results from CDA measurements on the open-cell flexible polyurethane foam (Figure 4) draw a unique picture for the elastic behavior of the material. It clearly shows that one single value of Young's modulus from quasi-static experiments does not represent the elastic property of the material at different strains. The initial value of the storage modulus is close to the quasi-static Young's modulus. However, the foam walls become stiffer with increasing amount of bending, which causes the storage modulus to increase, until the critical stress for elastic buckling is reached. In Regime II, the decrease in storage modulus is consistent with the proposed buckling mechanism. Finally, the storage modulus increases with strain in Regime III, as the foam starts to densify. It is reasonable to infer that the measurement of elastic modulus at each and every point of strain should enable us to better simulate the properties of cellular materials.

Unlike the storage modulus, the loss modulus does not change significantly during Regimes I and II. In Regime III, the loss modulus also increases along with the storage modulus, which should reach the properties of solid polyurethane at much higher strains. The inset in Figure 4 shows the change in the loss factor, defined as E''/E', with increasing strain. Initially the loss factor decreases as the foam wall get stiffer upon bending. The increase of loss factor upon further deformation (Regime II) suggests that the buckling of foam walls is the dominant mechanism for the energy dissipation.
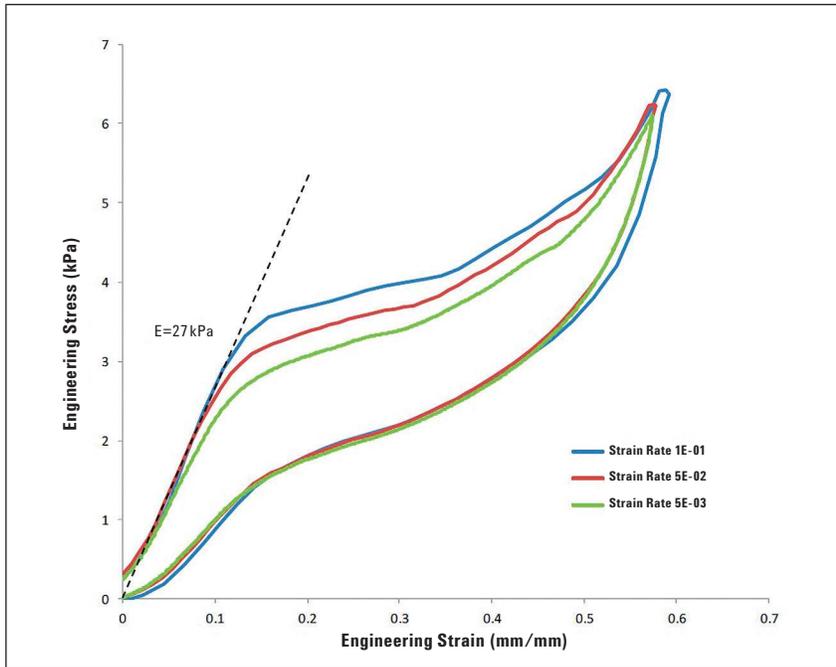
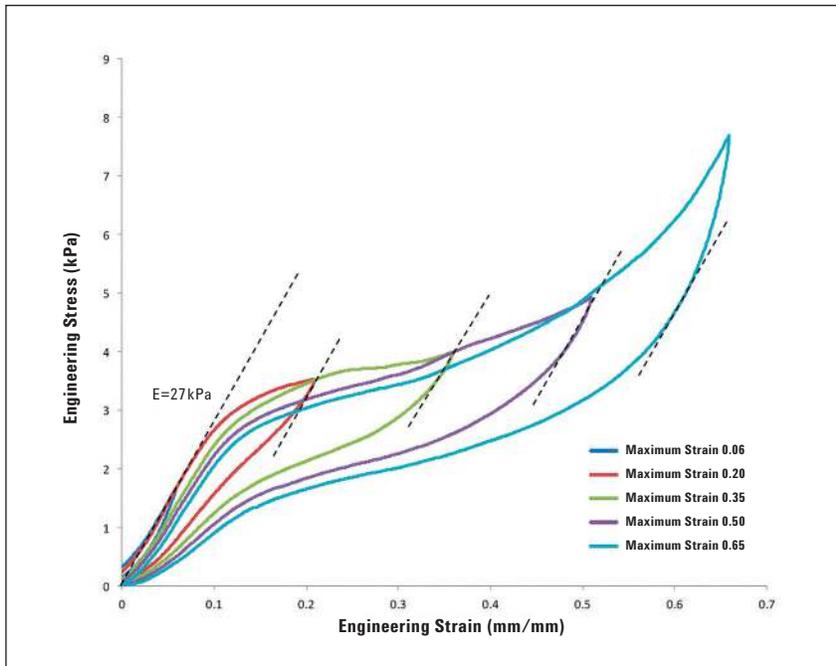Figure 5. Effect of strain rate on the engineering stress-strain response of flexible polyurethane foam.

Figure 6. Cyclic compressive deformation of flexible polyurethane foam, with increased maximum strain at subsequent cycles. Note the dashed lines represent the measured Young's modulus of 27 kPa.

Figure 5 exhibits the effect of strain rate on the compression behavior of open-cell polyurethane foam. Although the initial linear elastic response stays almost similar at different strain rates, the critical stress for elastic buckling increases with increasing strain rate. The effect of strain rate also decreases significantly once the foam starts to densify. Figure 5 suggests that the elastic buckling mechanism in polyurethane foam walls is dependent on strain rate. The distinction in the strain rate effect among the three deformation regimes of the foam is extremely important for designing flexible cellular materials for applications in tissue scaffolds.

The buckling of foam walls during Regime II is noted as elastic because of the fully reversible nature during unloading. However, considerable amount of energy is dissipated during cyclic loading as can be seen in all the stress-strain curves. The strain-rate dependent nature of elastic buckling of foam walls is also consistent with the hysteretic behavior in this regime. Figure 6 shows the nature of hysteretic behavior at different strains up to a maximum strain of 0.65. The reason behind the difference in loading curve for each cycle is not clear at this point, but is most probably due to the broken struts near the surface, which causes small residual plastic strain after unloading. However, it is clearly evident that the amount of energy dissipation increases with increasing strain. The increase in elastic modulus of the material in Regime III is also evident from the slopes of initial unloading part of stress-strain curves (dashed lines in Figure 6). This again implicates the importance of using the continuous dynamic analysis for mechanical characterization of cellular solids.
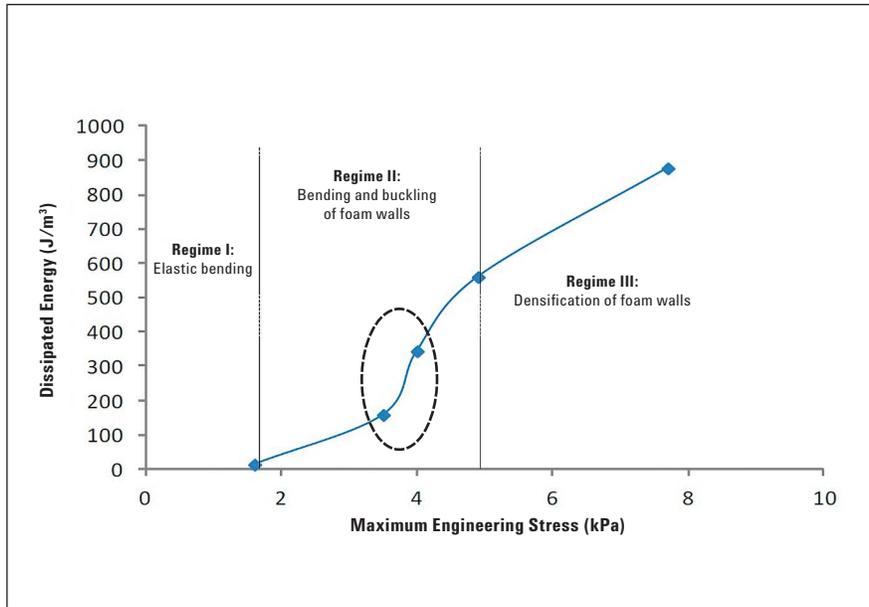
Figure 7. Variation in energy dissipation with increased maximum strain during cyclic compression. Note the high slope in the circled region, where the elastic buckling is most active.

The energy dissipation for each cycle is calculated from:

$$W_d = \int_0^{\epsilon_{max}} \sigma d\epsilon + \int_{\epsilon_{max}}^0 \sigma d\epsilon \quad (6)$$

where, ϵ_{max} is the maximum strain during cyclic loading.

The change in energy dissipation of the flexible polyurethane foam specimen with increasing stress is shown in Figure 7. As expected, the elastic bending of foam walls in Regime I dissipates negligible amount of energy. The intercept on the stress axis represents the critical stress for elastic buckling, which is close to the critical stress observed in Figure 3. The rate of energy dissipation in the Regime II increases as the foam walls, parallel to loading axis, starts to buckle. This behavior is consistent with the change in loss factor (inset of Figure 4). Once the foam walls start to densify, the rate of increase in energy dissipation drops

again. This behavior suggests that the foam wall buckling has the largest contribution towards total energy dissipation during compression of the foam.

Summary and Conclusions

In conclusion, the Keysight UTM T150 with a new NanoSuite test method has been demonstrated to successfully perform quasi-static and dynamic compression tests of flexible polyurethane foam. The Young's modulus of 27 kPa, determined from the present experiments, matches well with previously reported values in the literature. However, the continuous dynamic analysis during the compression tests show that the elastic properties of the polyurethane foam change with strain. The compressive deformation in polyurethane foam

shows three main regimes due to elastic bending, elastic buckling and densification of foam walls. The elastic buckling mechanism is the most sensitive to the change in strain rate, and dissipates the maximum amount of energy.

Significance

It is shown for the first time that the CDA option in the Keysight UTM T150 is an important tool to characterize elastic properties of flexible cellular solids. The new quasi-static and dynamic tests will be extremely useful to systematically study the mechanical properties of soft porous materials (e.g., soft tissue scaffolds for biomedical applications — where the elastic modulus has a major influence on cell proliferation and growth) [12, 13].

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