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Compressed Elastomer Method for Internal Pressure Testing

by Robert Carter

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14. ABSTRACT The compressed elastomer method is a safe and easy technique for generating high internal pressure for tubular samples. The approach compresses a cylinder of an elastomeric material and uses the Poisson’s expansion to generate internal pressure. The equations needed to convert the axial force to the internal pressure are derived and the procedure is verified using a steel control sample. To date, pressures have been generated in excess of 340 MPa (50 ksi).			
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Contents

List of Figures

1. Introduction

High pressures are necessary to test tubes fabricated from structural materials. The methods used to achieve these high pressures can create dangerous conditions in the laboratory. High-pressure gases or fluids require extensive safety equipment to maintain and contain the pressure during and after the experiment. A safer means to create pressure is desired.

A safer and simple method to generate high-pressure conditions for pressure testing small-diameter tubes is the compressed elastomer method. It uses a piston to compress an elastomeric cylinder or plug inside a tube of material. The resulting Poisson's expansion will generate pressure along the inner wall of the tube sample. One of the attractive attributes of this test is that once the sample fails, the elastomer easily compresses and quickly lowers the stress and pressure in the system. There are no high-pressure gases or fluids to contain. Also, the use of a solid material to generate the internal pressure removes the need for high-pressure seals.

In this work, the compressed elastomer technique, as described in Singh et al. (*1, 2*) and further developed by Carter (*3*) and Carter and Swab (*4*), was utilized for the internal pressure tests. A schematic of the test is found in figure 1, and a photograph of the actual fixturing is in figure 2. Compression platens are used to compress the elastomeric material inside the tubular sample. The Poisson expansion resulting from the compression generates pressure on the inner surface.

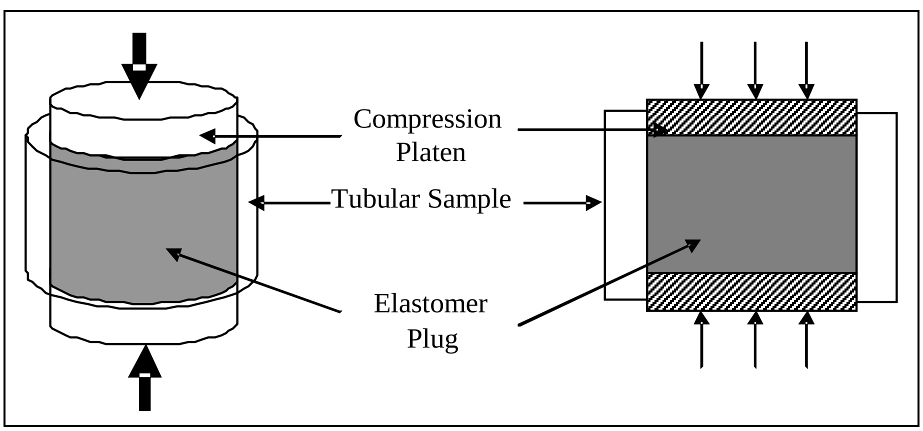

Figure 1. Schematic of internal pressure test with a cut-away.

For brittle materials, the testing should be performed in such a way to avoid loading too closely to the edge of the sample. This is significant so as not to apply axial loading due to the plug "mushrooming" over the edge, induce an edge effect, or edge-induced failure.* While

*Cutting brittle materials may introduce a new flaw population at the cut edges, which could skew the data by triggering failure at lower levels. In composite materials, it is possible to have different material properties near a cut edge due to the critical length of load transfer between the matrix and fiber.

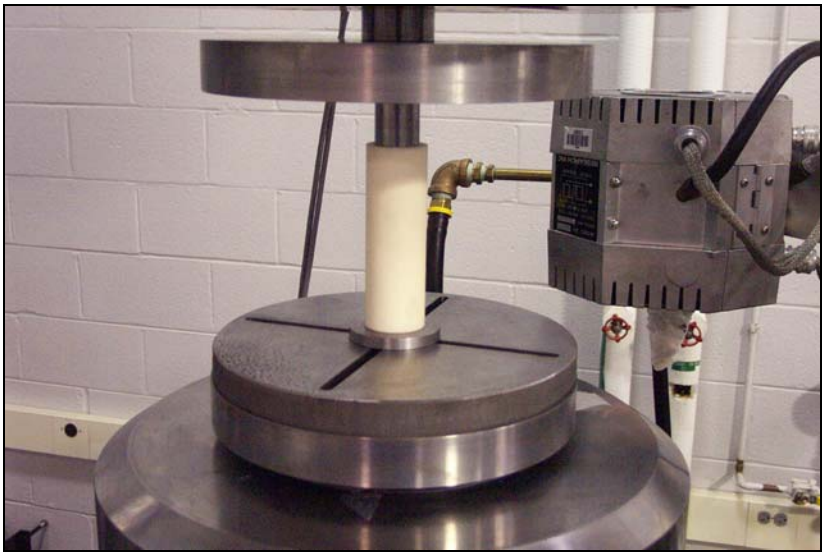

Figure 2. Compression test fixtures in a test frame.

pressurizing the middle section of a tube generates a non-uniform stress state along the length of the sample, the stress at the edges can be significantly lower than that in the gage section. While this prevents edge-induced failure, finite-element modeling is necessary to determine the geometric conditions (length of the sample and length of the unloaded sections near the edges for a given wall thickness) required for the stress state in the gage section to return to that of a uniformly pressurized tube.

Another area for concern is that the polymer can extrude into the gap between the compression platen and the sample. The pressure necessary for this is dependant upon the size of the gap and the stiffness of the elastomer. For these studies, the platen diameter was machined to be within 0.3 mm (0.01 in)* of the inner diameter of the samples. With this opening, the plug would extrude into the space between the platen and the sample for some of the higher-pressure tests (in excess of 100–150 MPa). When this occurred, the pressure would level off while the platen would continue to displace. The samples would not fail, and the platen would be difficult to remove when the sample was unloaded. To avoid the problem for high-pressure tests (in excess of 150–200 MPa for this apparatus), nylon spacers were inserted into the sample, as seen in figure 3. The goal of adding the spacers was to allow the Poisson's expansion of the nylon to fill the spaces and prevent the elastomer from extruding around the platen. Tests have been run well in excess of 300 MPa without showing any signs of extrusion of the plug.

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*A tighter fit was possible but this platen was designed to accommodate variations in the fit for a large number of samples.

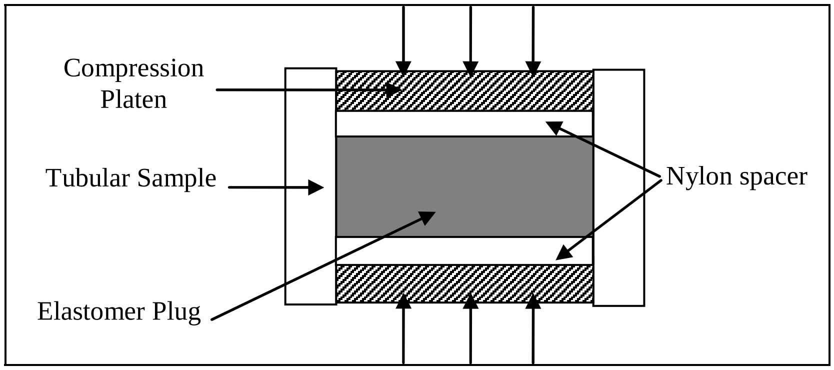

Figure 3. Schematic of a high-pressure internal pressure test configuration.

2. Axial Force to Internal Pressure Calculations

The pressure generated at the inner surface of the sample is related to the applied stress in the material. To analyze this situation, one starts with the Hooke's Law expression for the strain in the *x* direction (the axis of the cylinder), and simplifies it by recognizing that $\sigma_r = \sigma_\theta$ in axisymmetric conditions (*5*). Using this, the Hooke's Law expression for axial strain,

$$\varepsilon_x = \frac{1}{E_P}\left[\sigma_x - \nu_p\left(\sigma_r + \sigma_\theta\right)\right], \tag{1}$$

becomes

$$\varepsilon_x = \frac{1}{E_P}\left[\sigma_x - 2\nu_p\sigma_r\right]. \tag{2}$$

For the internal pressure-test sample, $\sigma_r = -P_i$ at the inner surface, which allows for the internal pressure equation to simplify to

$$P_i = \frac{E_p\varepsilon_x - \sigma_x}{2\nu_p}, \tag{3}$$

where P_i is the internal pressure, σ_x, E_p, ε_x, and ν_p are the compressive stress, Young's modulus, axial strain, and Poisson's ratio, respectively, for the plug material. This expression is derived from an elasticity solution for an isotropic, linear elastic material. For an incompressible, linear elastic material (ν_p = 0.5), the expression in equation 3 simplifies to

$$P_i = E_p\varepsilon_x - \sigma_x \tag{4}$$

or

$$P_i = \sigma_x^E - \sigma_x, \tag{5}$$

where σ_x^E is the elastic stress for a given ε in the plug. The dependence of the internal pressure on the stress state of the elastomer makes this test procedure attractive for small-diameter samples. The amount of axial compressive force needed to generate a given pressure is significantly smaller for small-diameter tubes than it would be for a large-diameter tube.

It is important to note that if large deformations are used for these tests, the engineering values for stress and strain are no longer correct, and true stress and strain values should be used for this procedure. These values are found from the engineering stress and strain values by

$$\begin{aligned} \tilde{\varepsilon} &= 1n\left(1+\varepsilon\right) \\ \tilde{\sigma} &= \sigma\left(1+\varepsilon\right), \end{aligned} \tag{6}$$

where $\tilde{\sigma}$ and $\tilde{\varepsilon}$ are the true stress and strain and σ and ε are the engineering stress and strain (*6*). A plot of the stress-strain behavior of Dow Corning Silastic* silicone rubber for a compression test is included in figure 4. The three lines are the engineering and true stress-strain curves and the Mooney-Rivlin fit to the data. Linear regression analysis of the true stress-strain values yields a slope of 1.57 MPa and an $R^2 > 0.99$. Finding the Young's modulus in this way yields a different stress-strain relation:

$$E = \frac{\tilde{\sigma}}{\tilde{\varepsilon}} = \frac{\sigma\left(1+\varepsilon\right)}{1n\left(1+\varepsilon\right)}, \tag{7}$$

or

$$\sigma_x^E = \frac{E_p 1n\left(1+\varepsilon_x\right)}{\left(1+\varepsilon_x\right)}. \tag{8}$$

By combining equations 5 and 8, the expression for calculating the pressure from the stress measurements for the internal pressure test procedure is

$$P_i = \frac{E_p 1n\left(1+\varepsilon_x\right)}{1+\varepsilon_x} - \sigma_x. \tag{9}$$

The σ_x value is the applied stress to the plug and ε_x is the engineering strain.

If the elastomer used for the plug is incompressible (i.e., has a Poisson's ratio of 0.5), and the test begins with the plug in intimate contact with the inner surface of the sample, a hydrostatic state is generated with the application of pressure. By this, the internal pressure would equal the stress generated by the applied axial force. For the tests performed in this work, the plug diameter was

* Silastic is a registered trademark of Dow Corning, Midland, MI.

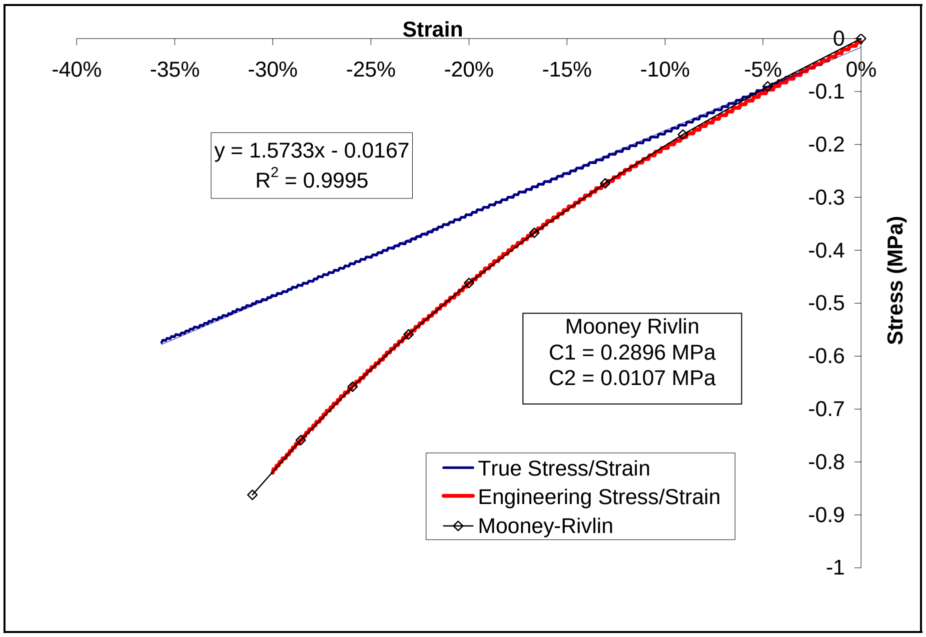

Figure 4. Compressive stress-strain curve for the Silastic plug. The curved line is the engineering stress-strain, and the other line is the true stress-strain plot with a best-fit line. The equation beside the best-fit line is its slope and R^2 value.

smaller than the inner diameter of the sample. This required a certain stress state in the material for contact to be made with the inner surface. By using equations 5 and 8, the contact stress can be subtracted out to leave the pressure value.

Other research has been conducted independently on this procedure at Oak Ridge National Laboratory, using similar procedures and materials (*7*). Instead of viewing the Silastic materials as a linear elastic material, hyper-elastic theory is used to describe the material response. This theory accounts for the nonlinear stress-strain behavior exhibited during large deformations of elastomeric compounds. There are several equations used to describe the behavior, but, for the Silastic compound, the Mooney-Rivlin equations are adequate to describe the deformation (as seen by the fit of the Mooney-Rivlin line to the data in figure 4). The resulting expression to describe the deformation is

$$\sigma_x^o = 2\left(\lambda - \frac{1}{\lambda^2}\right)\left(C_1 + \frac{C_2}{\lambda}\right), \tag{10}$$

where σ^o is the stress value using the original cross sectional area, C_1 and C_2 are constants fit to the data of an unconstrained compression test, and $\lambda=1+\varepsilon$ (*8*). Again, the pressure term is calculated by subtracting the σ^o stress value from the measured axial stress, as shown in equation 5.

3. Experimental Verification

To verify if this method is accurate in determining the internal pressure, a steel control sample was used since it allows for the calculation of the pressure by different methods. For the test, two strain gages were placed around the sample recording the hoop strain. The internal pressure was calculated using the linear elastic and hyper-elastic equations, and the values were checked by a pressure value found using a Lamé cylinder analysis of the experimental hoop strain (*5*). The hoop stress at the outer surface by the Lamé cylinder solution is

$$\sigma_\theta = \frac{2r_i^2 P_i}{r_o^2 - r_i^2}, \tag{11}$$

where r_i and r_o are the inner and outer radii and P_i is the internal pressure. Rearranging equation 11 to solve for the pressure value gives

$$P_i = \frac{E_s \varepsilon_H \left(r_o^2 - r_i^2\right)}{2r_i^2}, \tag{12}$$

with E_S being the Young's modulus of the steel and ε_H is the hoop strain. Figure 5 shows the pressure as a function of compressive axial force during the test. The three values are nearly superimposed onto each other and show sharp agreement. Figures 6 and 7 illustrate the response of the sample to the applied pressure. Figure 6 shows the strain response to the internal pressure, while figure 7 illustrates the same data but the pressure has been converted to a stress value, giving the material stress-strain curve from the test. The slope of the material is 199 GPa, which further supports the results since the modulus of steel is 200 GPa. Also, figure 7 illustrates two different pressurizations of the same sample. The first run ramped up and back down while still in the elastic range of the material. The second run follows the same loading curve, but continues well beyond the yield point of the sample.

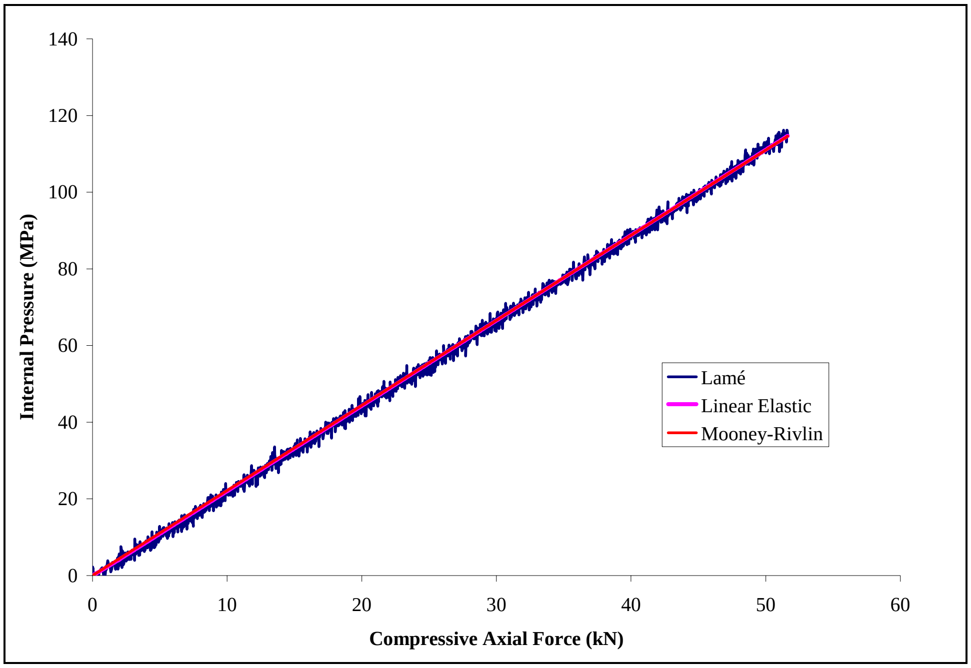

Figure 5. Results from the internal pressure test for the control sample. The different lines represent the pressure values found using the linear elastic, Mooney-Rivlin hyper-elastic, and Lamé cylinder solutions. The lines for the linear elastic and Mooney-Rivlin solutions are superimposed.

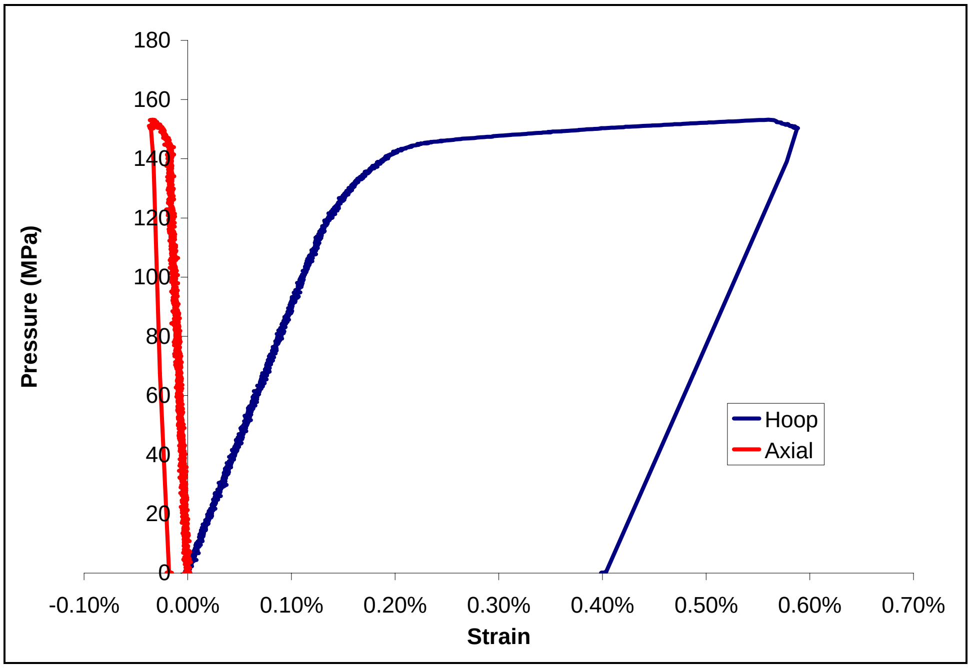

Figure 6. Strain response of the steel tube to pressurization.

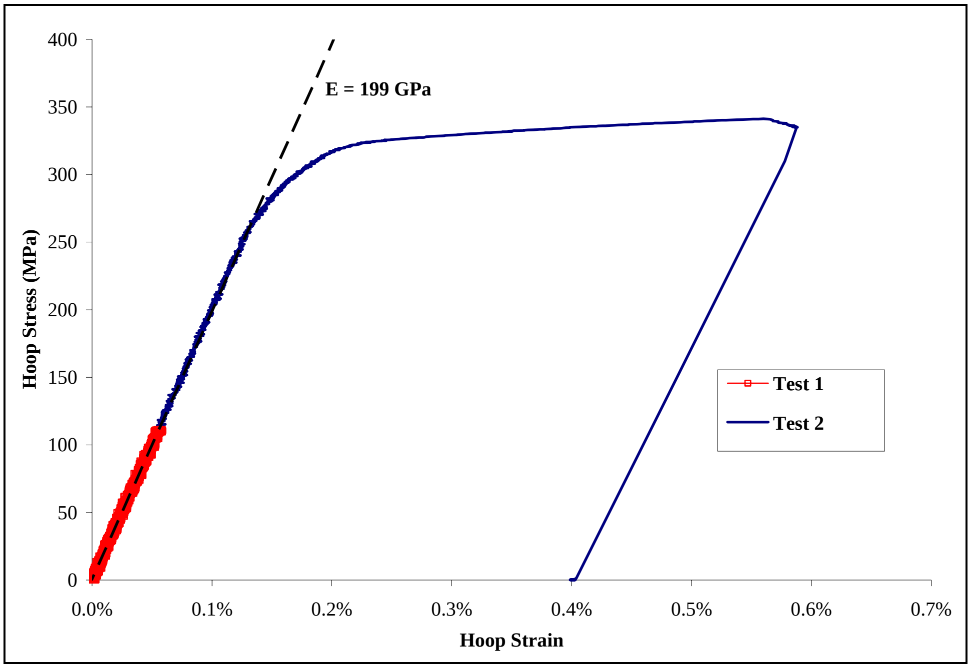

Figure 7. The stress-strain response of the steel tube.

The quick unloading of the solid plug is an attractive attribute to this procedure in that it allows the pieces of fractured samples to be captured. For the Ceramic Gun Barrel Program Army Technical Objective, this test was used to pressurize candidate ceramic tubes to failure (*4*). It was of interest to determine the origin of failure for each sample. The tests were conducted within a plastic confinement tube which was filled with foam rubber. The ceramic was wrapped with duct tape and placed within a hole cut in the foam rubber. Upon failure, the tape and foam contained the fragments, allowing for easy reconstruction of the tube for fractographic analysis. Minimal effort was needed to reassemble the sample in figure 8.

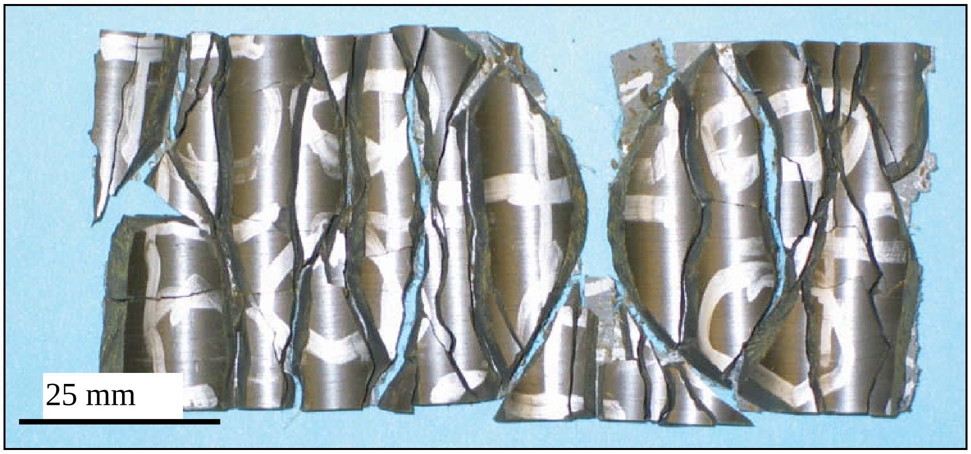

Figure 8. Fractured ceramic specimen.

4. Conclusion

The compressed-elastomer method is a simple approach to generating high pressures in tubular samples. The approach allows for converting compressive force to internal pressure without the need for high-pressure seals and/or high-pressure fluids or gases. The quick unloading of the sample upon fracture allows for easier collection of fragments and post-mortem analyses.

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