AE 3610, Lab #01

When a Dog Bone Becomes a Dalmatian Bone

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Group A11

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Introduction

Digital Image Correlation (DIC) is a technique that uses high-resolution cameras to capture the movement of a pattern on a specimen under strain. Scientists can then use specialized software to recognize the patterns and the correlate the stretch, skew, and translation of a pattern with associated strain. This method can replace the method where a strain gauge is placed physically on the specimen. The benefit of using DIC versus using the strain gauge method is that with DIC, one need not interfere with the specimen physically or chemically by attaching the strain gauge and that the strain gauge may have physical limitations. In this experiment, our group used DIC to measure the strains in two polypropylene specimens: a “dog bone” with a hole in it under an open-hole tensile test and a square prism rod under a four-point bending test. Traditionally, the patterns for the software to recognize are applied to a specimen by using a spray technique. However, due to time constraints, a piece of paper with a printed pattern was attached to each specimen because the paper printouts assured good data.

Data Results

Raw Data

<u>Four-Point Bending Test</u>

Our team measured the thickness and width of the rod specimen at 1.015 inches thick and 1.023 inches wide (Table 1). We placed the beam inside a four-point bending rig inside an Instron load frame (Fig. 1) and applied a load of 166.5 lbf. Using the specialized DIC software, Aramis, we took photos of the specimen before and after the load was applied.

<u>Open-Hole Tensile Test</u>

The team measured the thickness, width, and hole diameter of the dog bone specimen (0.255 in, 1.506 in, and 0.247 in respectively). We placed the dog bone specimen in the Instron and applied a load of 2.5025 kN. Using the specialized DIC software, Aramis, we took photos of the specimen at a neutral position, at a load of 2.0160 kN, and at 2.5025 kN.

Reduced Data

Four-Point Bending Test

Aramis software calculated the strain in the specimen in the horizontal and vertical directions. During the experiment, the paper speckle pattern buckled and tore in a few places. In large areas of buckling, the data was masked before exporting. Figures 7, 8, and 9 depict the horizontal, vertical, and shear strain in the test specimen as a false-color image created with the pcolor() function in MATLAB. Plots from Figures 10, 11, and 12 show the corresponding horizontal strain as we traverse through the polypropylene rod from the bottom to the top. We could calculate the elastic modulus of the material using the slope of the linear fits from Figures 10, 11, and 12 if the material were not polypropylene. Since polypropylene has different elastic moduli depending on whether in tension or compression, we must determine the elastic moduli through a more complicated method (Eqs 3 and 4). We can start out by fitting the linear equation below to the data in Figures 10, 11, and 12:

$$\varepsilon_x = -\kappa y - b \qquad \text{(Eq 1)}$$

Where κ the spring constant of the material and b an offset and the y and x are axes centered on the specimen. An average of the data resulted in a κ value of **0.0004 mm^{-1}** and a b value of **0.0011 strain.**

Using the b and κ values from (Eq 1), the neutral axis can be calculated as:

$$y_N = -b/\kappa \qquad \text{(Eq 2)}$$

Where the neutral axis lies **2.75 mm below** the vertical center of the specimen.

The equations to determine the tensile modulus and compressive modulus are as follows:

$$E_T = M / [I*\kappa*(1 - 2b/\kappa h)^2 \qquad \text{(Eq 3)}$$

$$E_C = M / [I*\kappa*(1 + 2b/\kappa h)^2 \qquad \text{(Eq 4)}$$

Where M is determined to be the applied Moment, calculated as a*P (Figure 2), where a is the distance of 4 inches (101.6 mm) between the two rollers (Figure 1) and P is the applied force of 166.5 lbf, or 740.6 N (Table 1). M therefore has a value of 666 lb-in, or 75.25 N-m.

I is the second moment of inertia of the beam:

$$I = (w*h^3)/ 12 \qquad \text{(Eq 5)}$$

w and h (Table 1) are both about 1 inch, and therefore I has a value of about 0.1.

From these calculations, Eqs 3 and 4, and the data taken from Aramis, **E_T has a value of 5.072 GPa, and E_C has a value of 5.070 GPa.**

Poisson's Ratio

Poisson's ratio is determined by finding the derivative of the vertical strain with respect to the axial strain:

$$\nu = -d\varepsilon_y/d\varepsilon_x \qquad \text{(Eq 6)}$$

This is the slope of the transverse strain with respect to axial strain at the center of the specimen. Using the slope of the linear fit from Figure 17 and multiplying by -1, **ν can be approximated as 0.33.**

Open-hole Tension Test

Using the elastic and compressive moduli of elasticity calculated from data found in the Four-Point Bending Test and the formula in Eq 7, we can calculate and show the strains on the specimen from the Open-Hole Tension Test (Figures 19 and 20).

$$\sigma = E\varepsilon \qquad \text{(Eq 7)}$$

Because polypropylene has different elastic moduli for tension and compression, it was necessary to multiply all the strain values that are greater than zero by E_T and all the strain values that were less than zero by E_C to obtain the images in Figures 19 and 20.

Tangential and radial stress were calculated using Eq 8 and 9, where σ_{rr} and $\sigma_{\theta\theta}$ are radial and tangential stress respectively. (See Figures 21 and 22.)

$$\sigma_{rr} = \sigma_x \cos^2\theta + \sigma_y \sin^2\theta + \sigma_{xy} 2\sin\theta\cos\theta \qquad \text{(Eq 8)}$$

$$\sigma_{\theta\theta} = \sigma_x \sin^2\theta + \sigma_y \cos^2\theta - \sigma_{xy} 2\sin\theta\cos\theta \qquad \text{(Eq 9)}$$

Average tangential stress away from the open hole was calculated by masking the stress field for values where the radius away from the center of the hole was over 7 millimeters. This average stress was calculated **at 104 kPa** for the 2.0 kN loading and **141 kPa** for the 2.5 kN loading.

Discussion

Supplement Questions

<u>Accuracy of results</u>

The relative difference between the calculated tensile modulus of elasticity and compressive modulus of elasticity seems to be low at a mere **0.0044 GPa** (4.4 MPa) of difference. However, if we look at where the neutral axis lies, it seems that what is calculated is not far from reality:

both the calculated and the real neutral axis seem to be around 2.5 to 3 millimeters below the middle of the specimen (Figure 7). I would use that metric to describe our team's measurements as reliable.

Within the published data from matweb.com for polypropylene, there is a very large range for the modulus of elasticity (Table III). The number calculated from the team's measurements of the tensile elastic modulus falls within that range, as it is incredibly large.

From the same source, the compressive modulus was only 1.38 GPa with no range given, whereas our team's measurements lead to a calculation of compressive modulus of over 5 GPa. (Table III). Without knowing where our specimen came from or how it was manufactured, it is difficult to remark as to the disparity between these two measurements.

It is of note that in both the published numbers on matweb.com and in our team's measurements, the tensile elastic modulus is generally higher than the compressive elastic modulus. Our team's measurements follow the same trend as the published results in that respect.

Photoelasticity method

Photoelasticity might be able to be used to measure the deformation of polypropylene, however the technique hinges on being able to "see" through the material as well as knowing how light behaves through the material. Perhaps if a smaller-wavelength light were used (X-rays), we could see through the material and get a picture of how the deformation is happening.

Additional Discussion

It is difficult to find information on the internet about polypropylene's two different moduli. The source that I found that listed two different elastic moduli was for "molded" polypropylene (as opposed to "extruded" or other types of polypropylene). It seems the mechanical properties of polypropylene vary greatly depending on manufacturing technique. Therefore, it is prudent to withhold judgement of our team's results given that there are so many unknowns: how was our specimen were manufactured? Why is there such a large range for the elastic modulus on matweb.com? What about "molded" polypropylene causes it to have two different moduli as opposed to polypropylene manufactured by other means?

Another item of further potential inquiry is that matweb.com's published measurements for the elastic moduli do not list the techniques used to achieve those measurements.

Tables and Figures

Table I. Measurements of the rod specimen in inches, taken with calipers and averaged along with load applied versus number of photos taken.

Number	Measurements (in)		Load applied (lbf)
	Thickness	Width	
1	1.014	1.021	**0.0**
2	1.016	1.024	**166.5**
3	1.016	1.026	
Average	**1.015**	**1.023**	

Table III. Measurements of the dog bone specimen in inches, taken with calipers and averaged along with load applied versus number of photos taken.

Number	Measurements (in)		Load applied (kN)
	Thickness	Width	
1	0.253	1.503	**0.000**
2	0.255	1.509	**2.016**
3	0.256	1.506	**2.503**
Average	**0.255**	**1.506**	

Table III: Calculated and values of κ, b, E_T, E_C, and Poisson's ratio along with published values of E_T and E_C

Measured/Calculated Properties of Polypropylene						
Kappa m^{-1}	b	E_T (GPa)	E_C (GPa)	Published E_T (GPa)	Published E_C (GPa)	Poisson's ratio
0.4	0.0011	5.0722	5.0678	0.008 - 8.25*	1.38*	0.33

*Source: https://matweb.com/

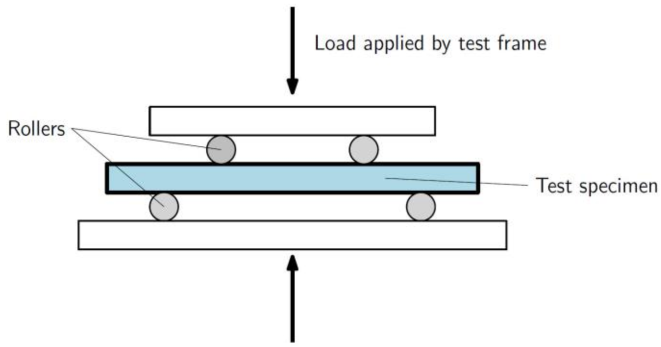

Figure 1. Testing rig for the rod specimen four-point bending test (source: gtae.gitbook.io./ae3610/).

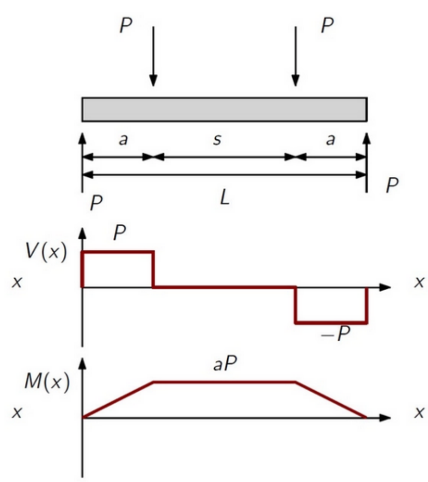

Figure 2: Chart depicting the moment applied in the four-point bending experiment (source: gtae.gitbook.io./ae3610/).

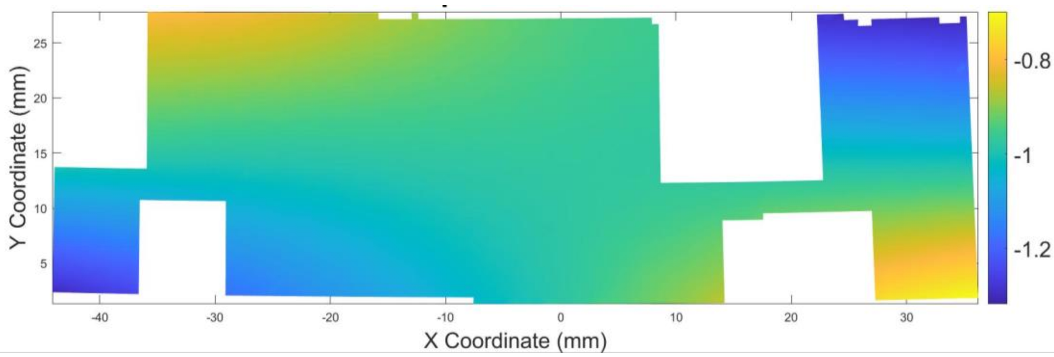

Figure 3: False-color image of rod specimen used during the four-point bending test. Color measures horizontal displacement. Outlier data due to buckling of speckle-paper has been removed, resulting in large squares. Colorbar units are millimeters.

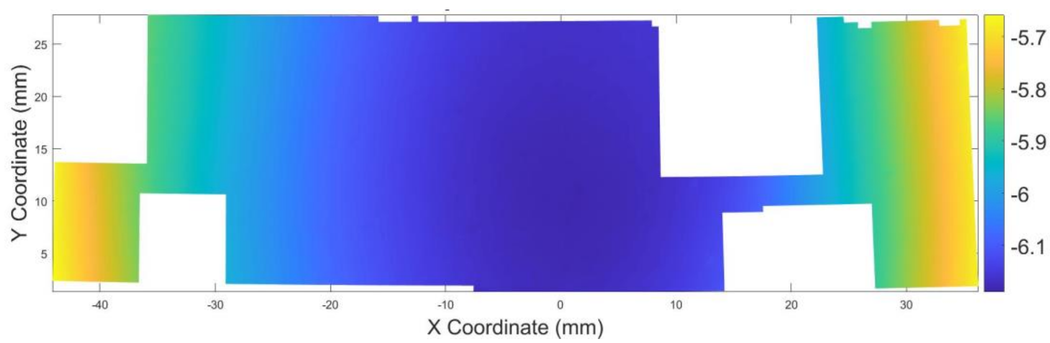

Figure 4: False-color image of rod specimen used during the four-point bending test. Color measures vertical displacement. Outlier data due to buckling of speckle-paper has been removed, resulting in large squares. Colorbar units are millimeters.

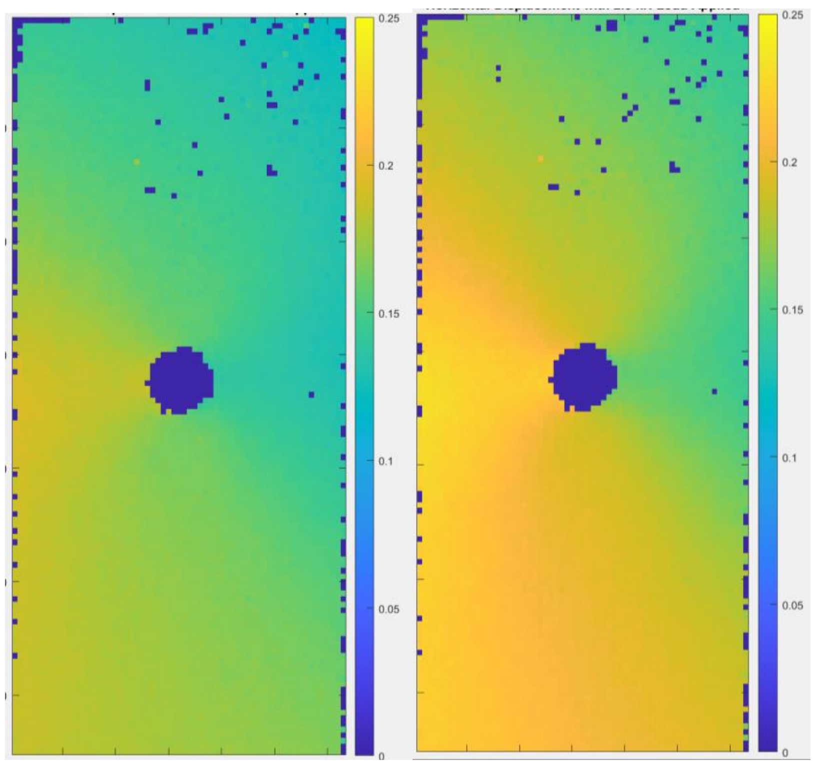

Figure 5: False-color image of horizontal displacement of dog bone specimen used in open-hole test. To the left is at a load of 2.0 kN and to the right is a load of 2.5 kN. Colorbar units are millimeters.

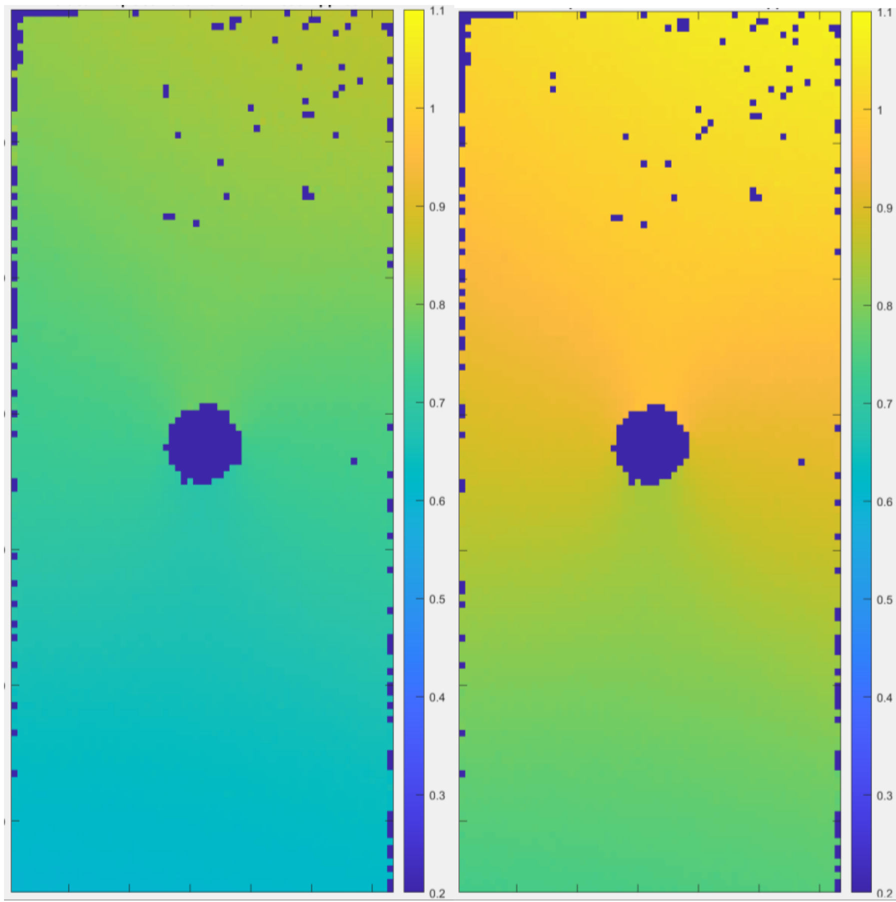

Figure 6: False-color image of vertical displacement of dog bone specimen used in open-hole test. To the left is at a load of 2.0 kN and to the right is a load of 2.5 kN. Colorbar units are millimeters.

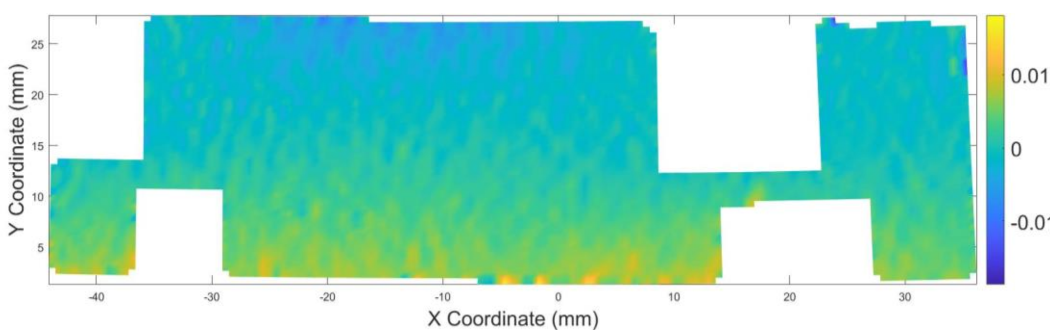

Figure 7: False-color image of ε_x (horizontal strain) calculated by Aramis and scaled to accentuate values. Colorbar units are strain.

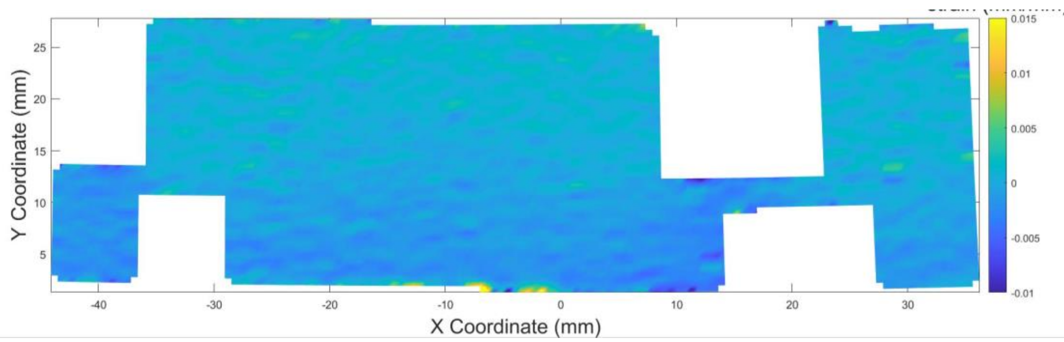

Figure 8: False-color image of ε_y (vertical strain) calculated by Aramis and scaled to accentuate values. Colorbar units are strain.

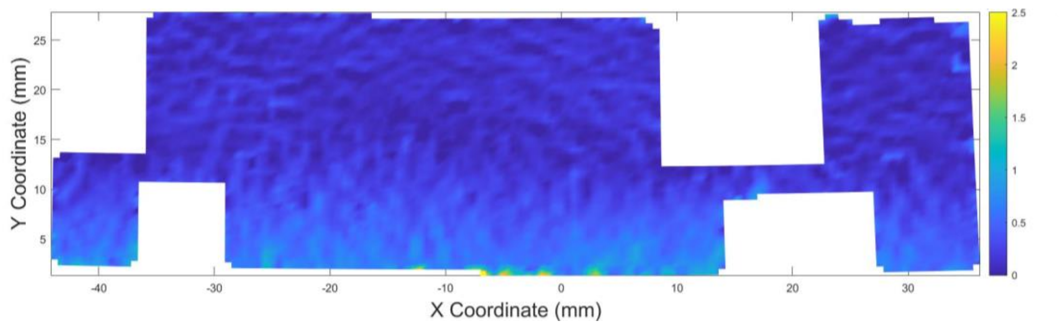

Figure 9: False-color image of γ_{xy} (shear strain) calculated by Aramis and scaled to accentuate values. Colorbar units are strain.

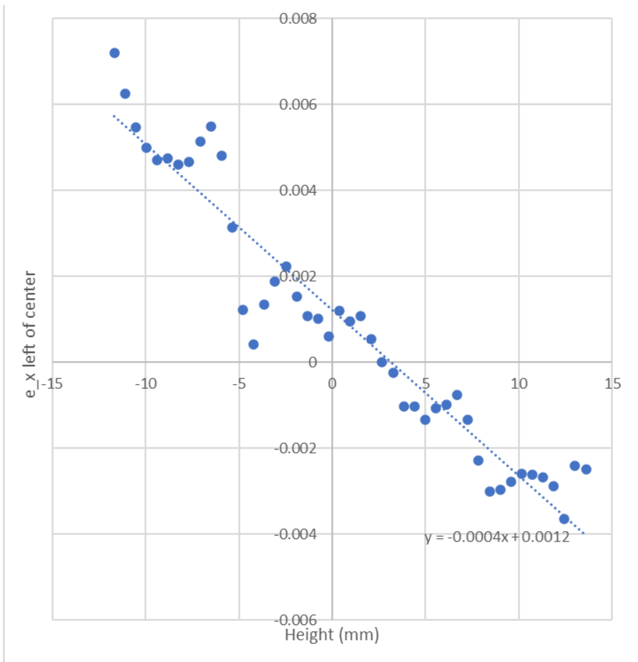

Figure 10: Horizontal strain calculated at a position slightly left of axial center plotted against height with 0 as the vertical center.

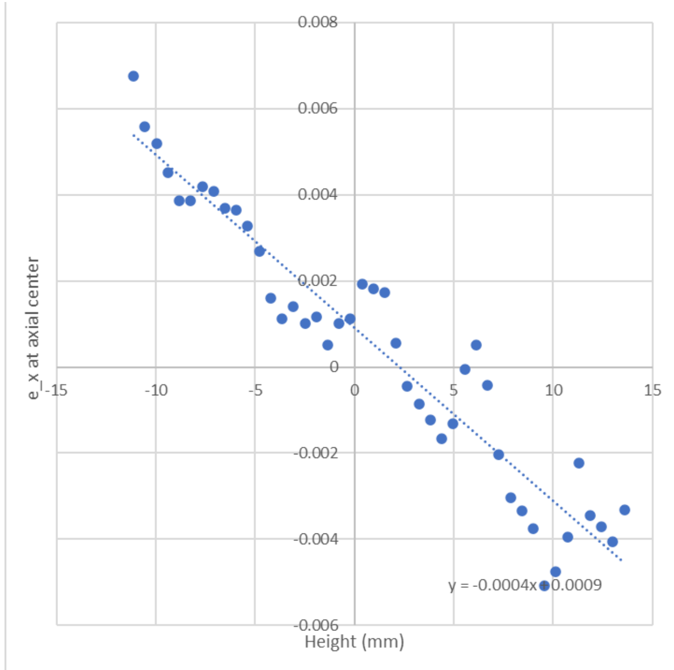

Figure 11: Horizontal strain calculated at a position at axial center plotted against height with 0 as the vertical center. Excludes outliers caused by inadequate masking of data.

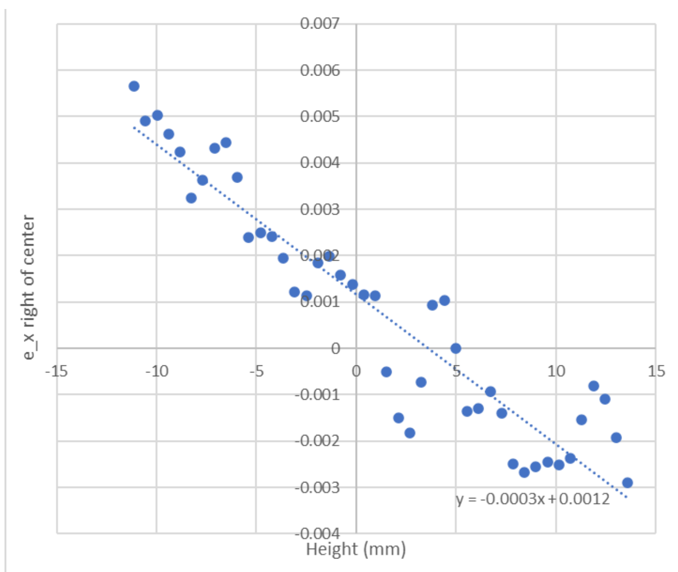

Figure 12: Horizontal strain calculated at a position slightly right of axial center plotted against height with 0 as the vertical center. Excludes outliers caused by inadequate masking of data.

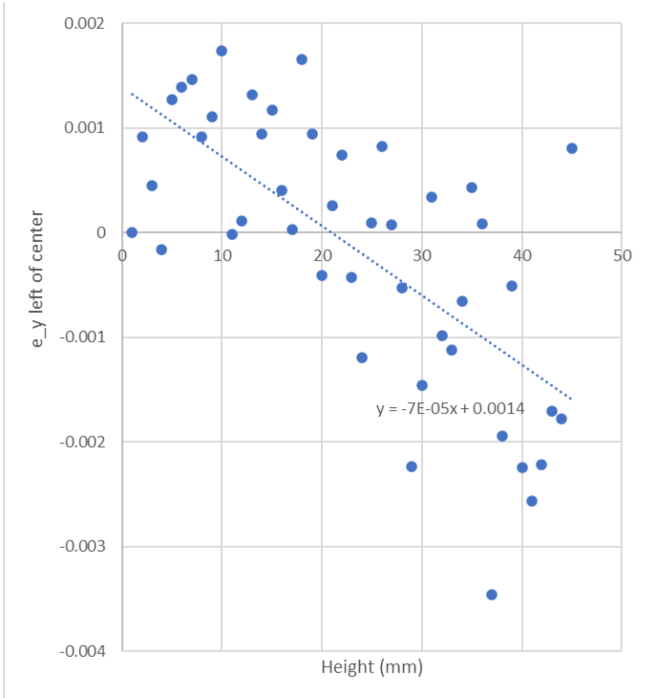

Figure 13: Vertical strain calculated at a position slightly left of axial center plotted against height with 0 as the vertical center.

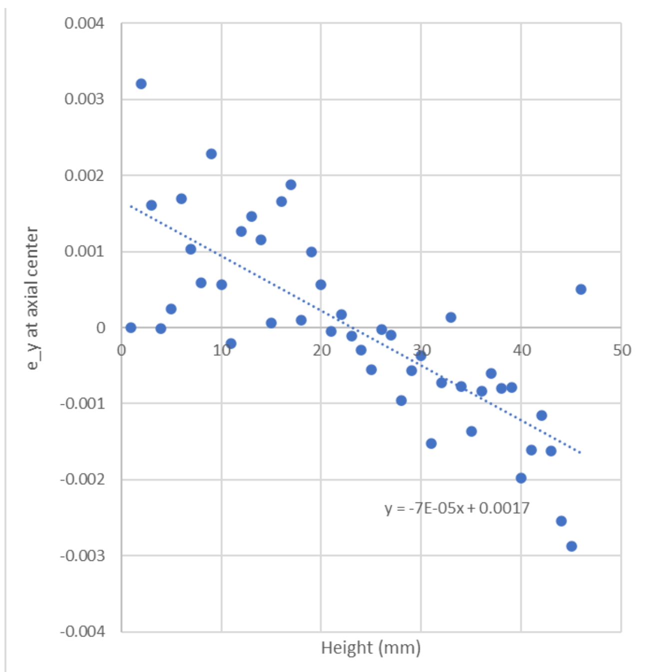

Figure 14: Vertical strain calculated at a position at axial center plotted against height with 0 as the vertical center.

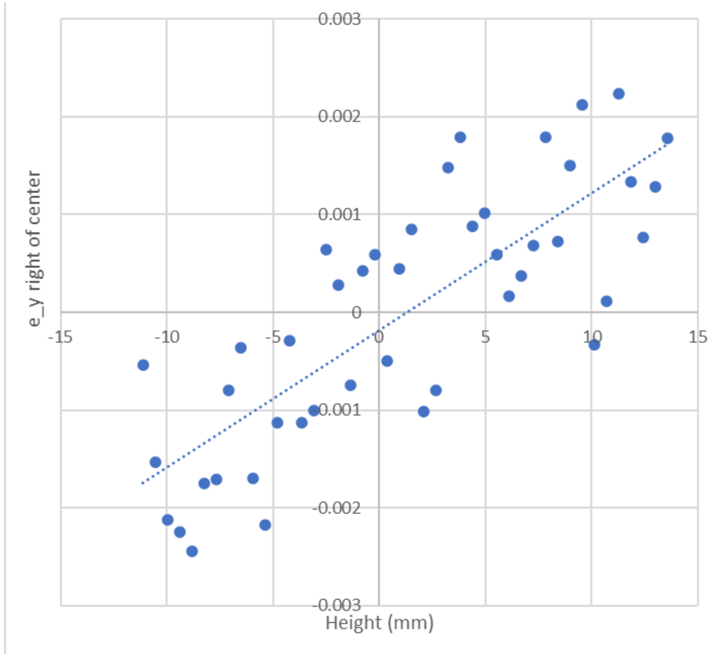

Figure 15: Vertical strain calculated at a position slightly right of axial center plotted against height with 0 as the vertical center.

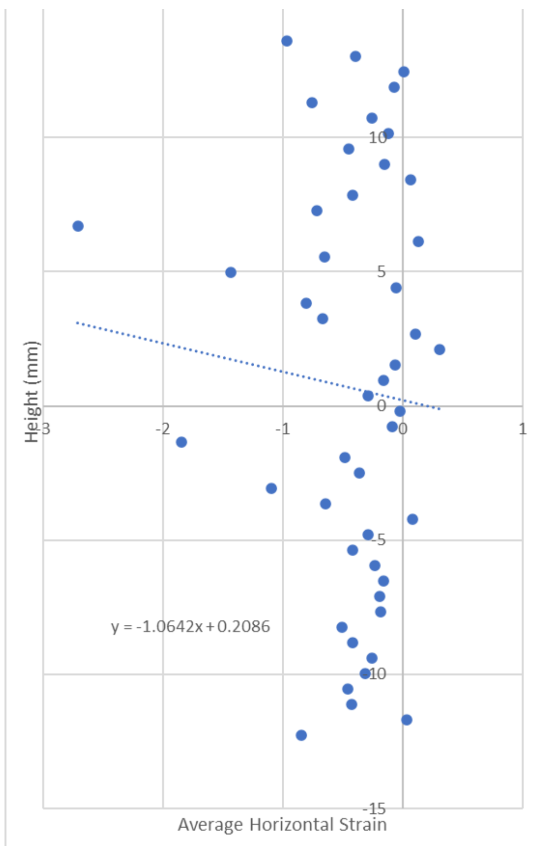

Figure 16: A plot of the Transverse normal strain (vertical strain) divided by the axial strain (horizontal strain) through the axial center of the specimen.

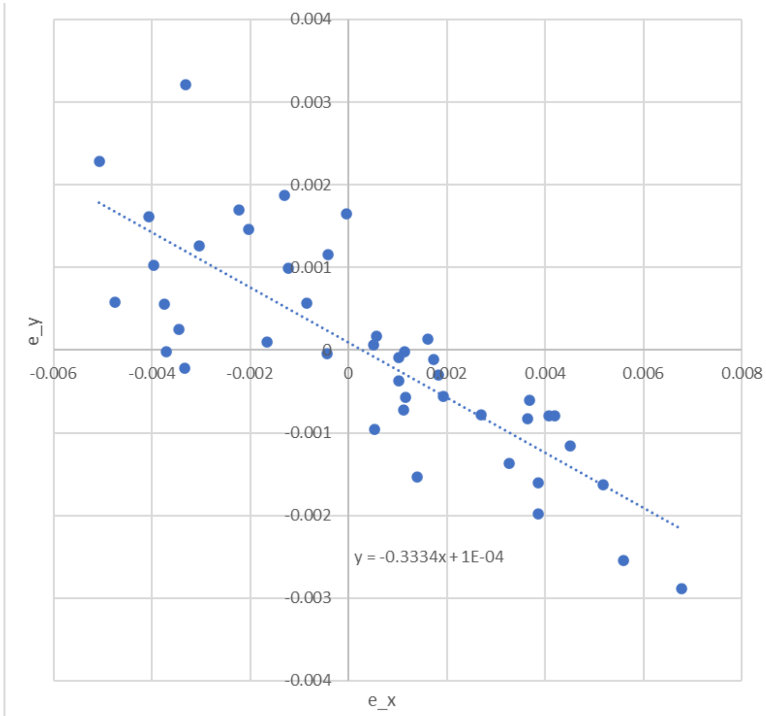

Figure 17: Transverse strain (ε_y) plotted as a function of axial strain (ε_x) along the center of the specimen.

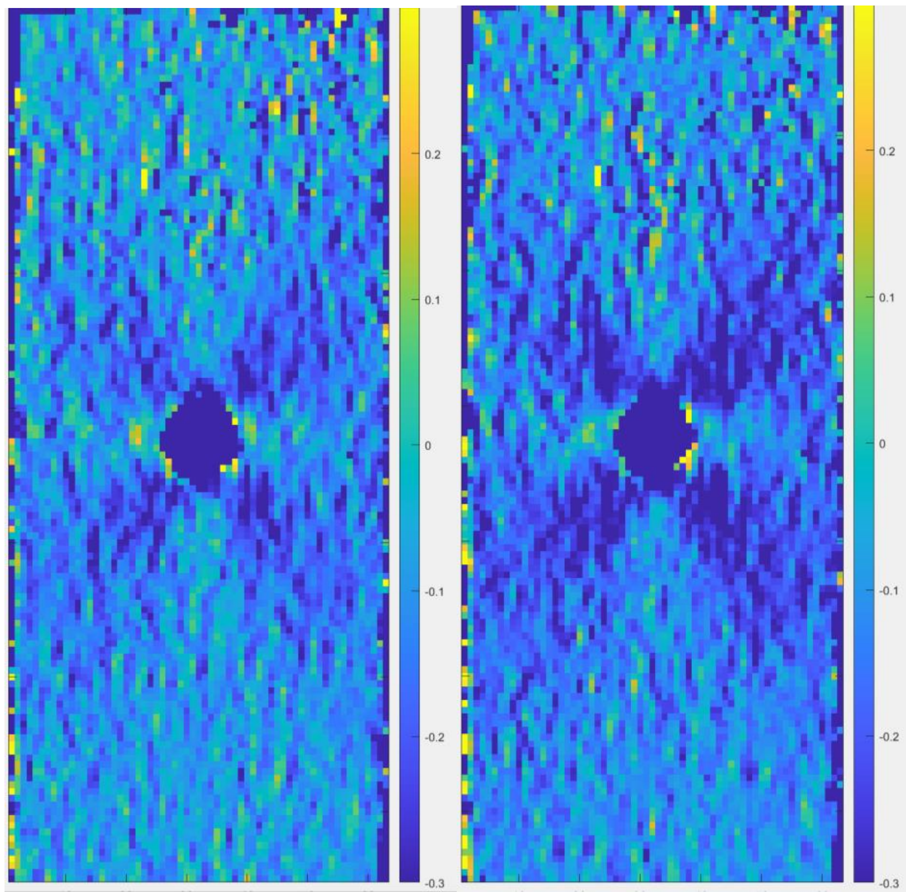

Figure 17: False-color images depicting the axial (horizontal) strain percent fields in both loadings of the dog bone specimen.

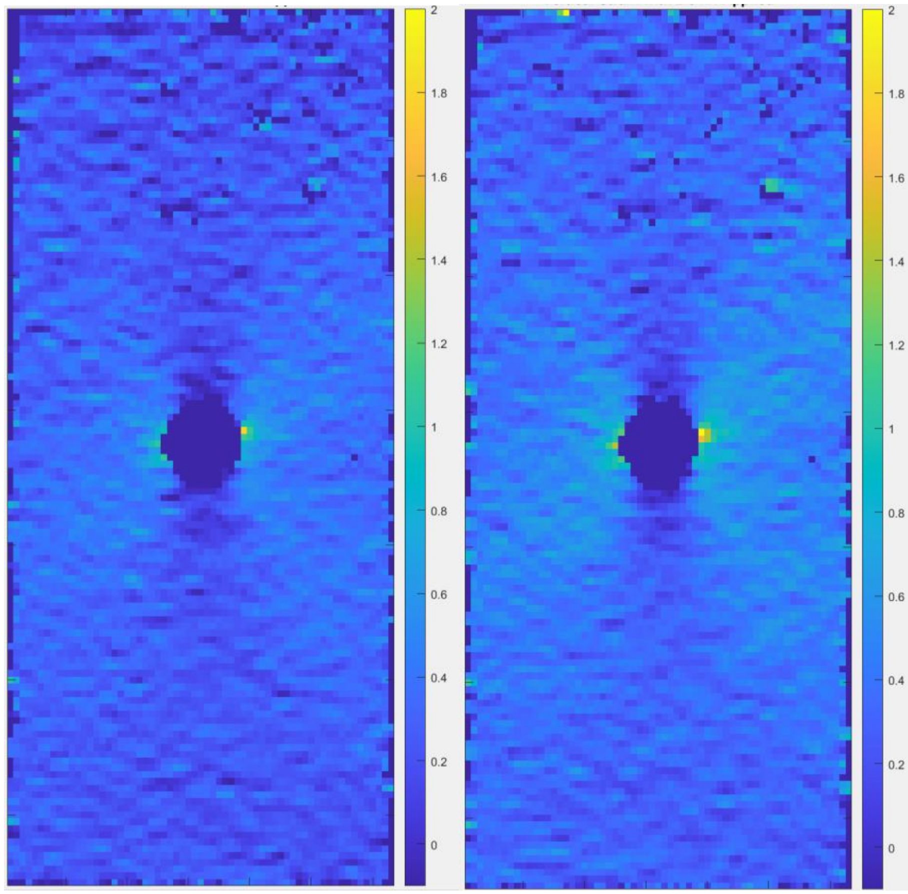

Figure 18: False-color images of the transverse (vertical) strain percent fields for both loadings of the dog bone specimen.

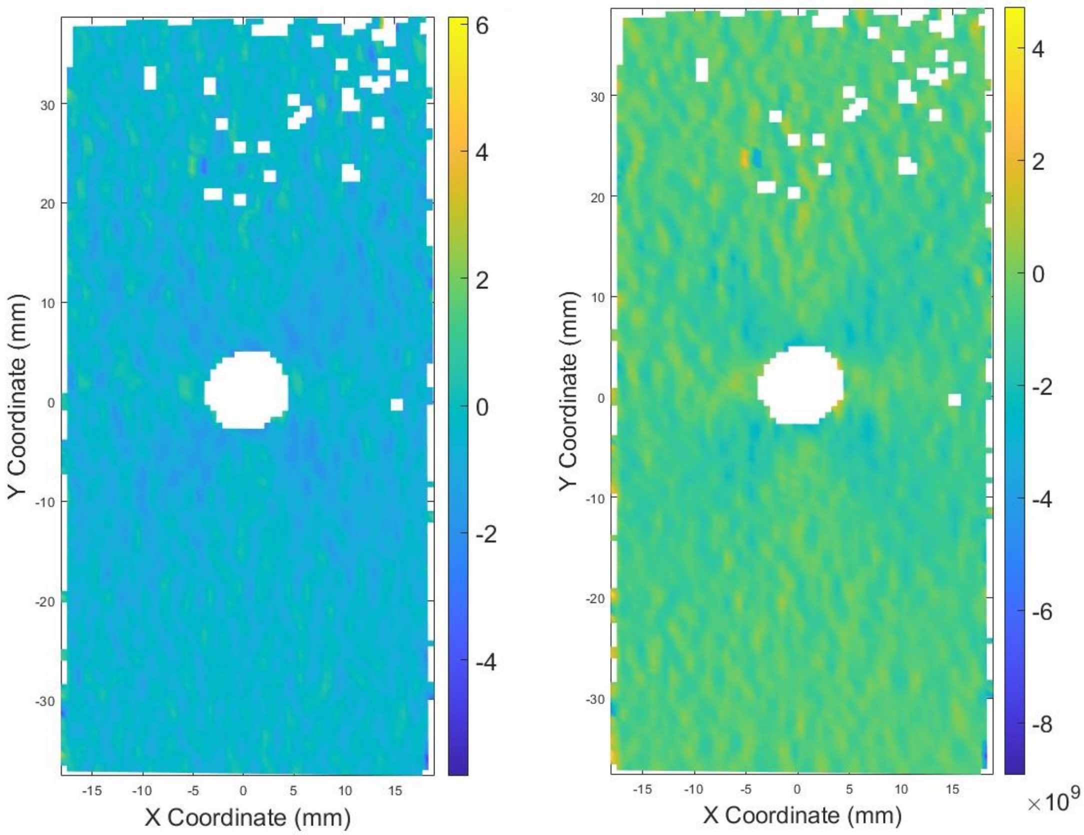

Figure 19: Horizontal stress (X stress, or σ_x) of the dog bone specimen under two different loadings during the open-hole tensile test shown with false color. Colorbar units are in GPa.

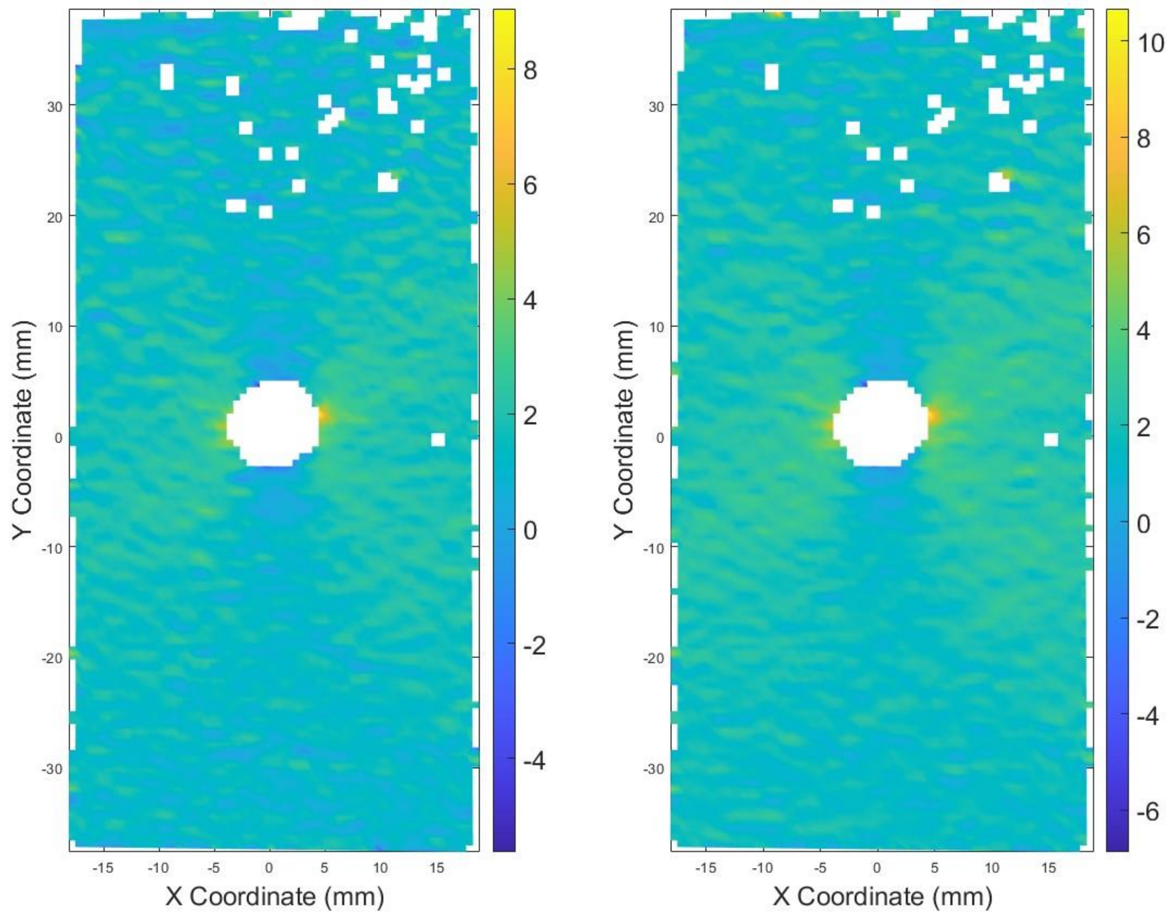

Figure 20: Vertical stress (Y stress, or σ_y) of the dog bone specimen under two different loadings during the open-hole tensile test shown with false color. Colorbar units are in GPa.

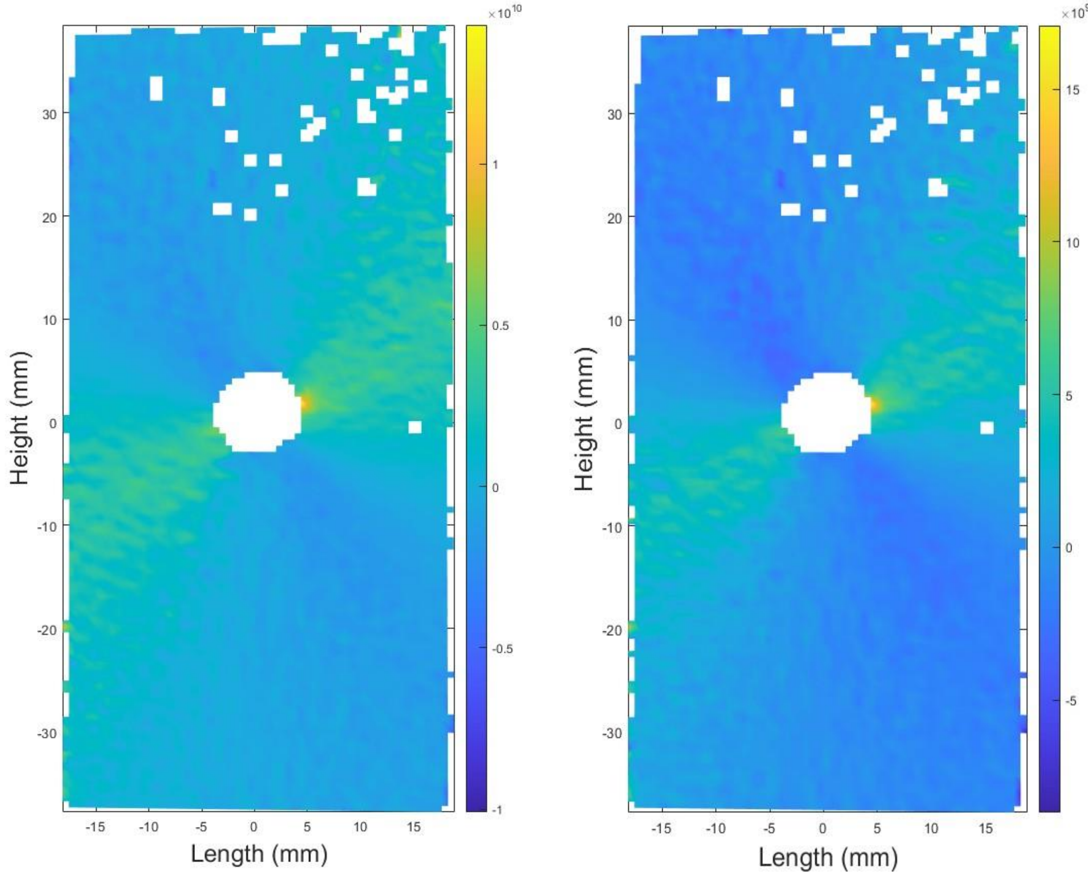

Figure 21: False-color image of the normal radial stress (σ_{rr}) field for the open-hole tensile test for both the 2.0 kN and 2.5 kN loading.

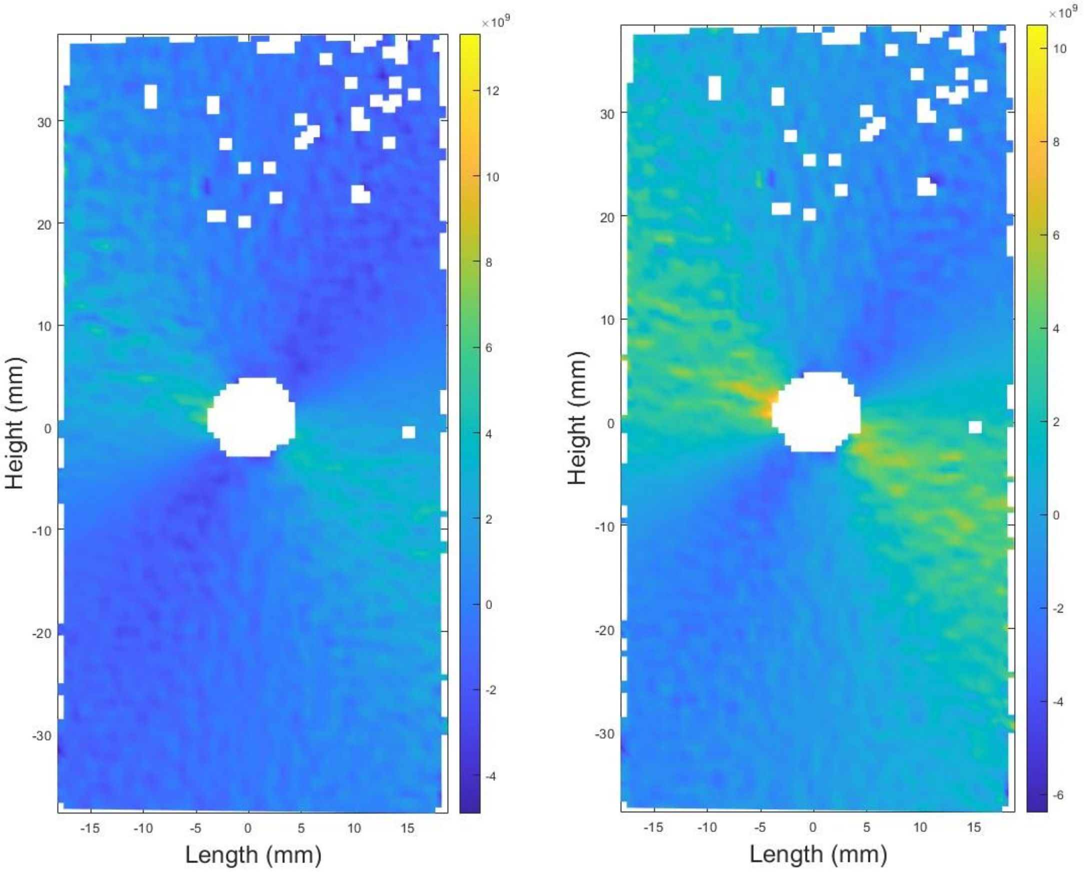

Figure 22: False-color image of the normal tangential stress ($\sigma_{\theta\theta}$) field for the open-hole tensile test for both the 2.0 kN and 2.5 kN loading

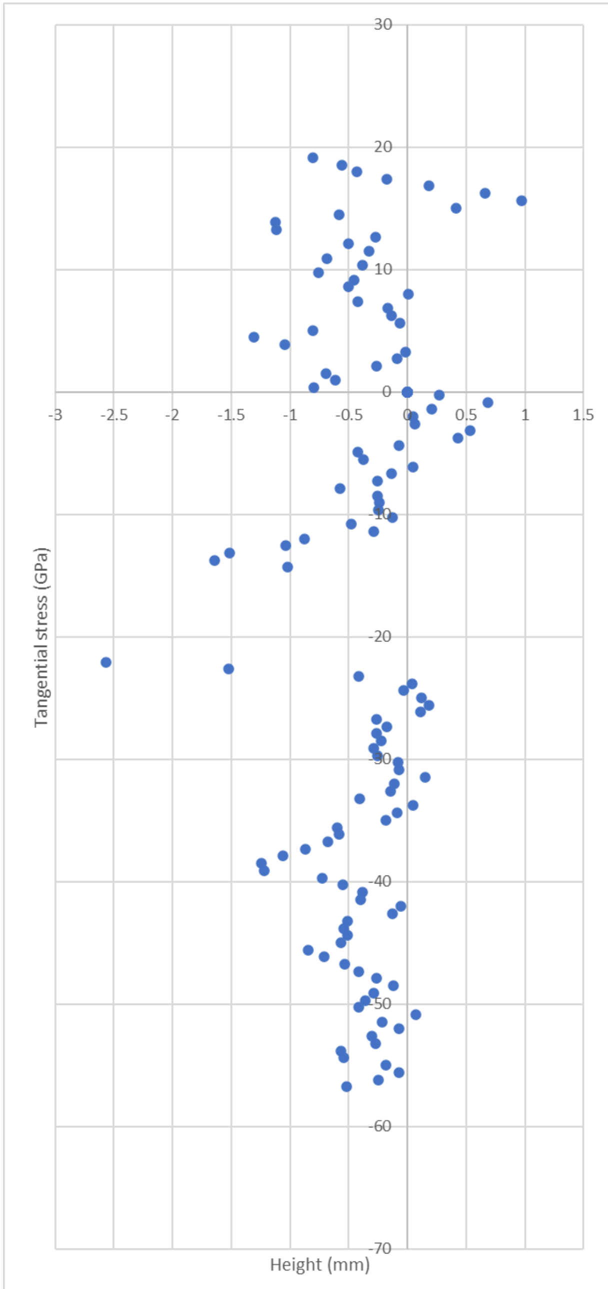

Figure 23: Plot of the tangential stress along a line in the vertical direction passing through the center of the hole for the 2.0 kN and 2.5 kN loading.

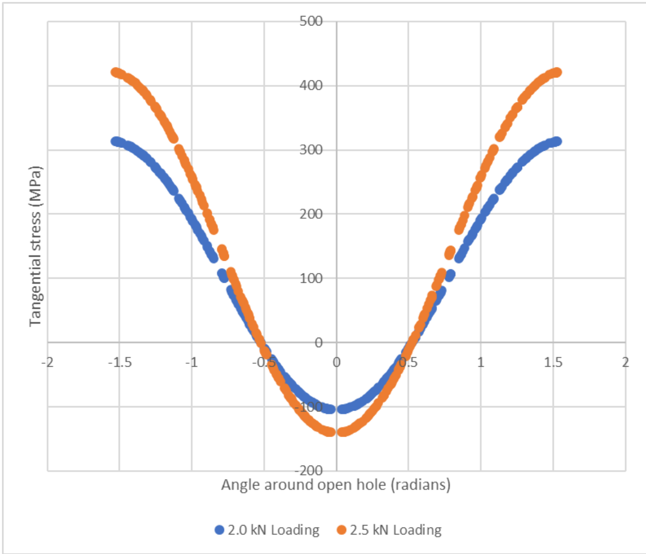

Figure 24: Plot of the tangential stress (normalized by its value far from the hole) as a function of the angle around the hole, close to the edge of the hole. Represents both the 2.0 kN and the 2.5 kN loading