Strain Measurement Methods for Elastic Modulus Determination

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Quartus Engineering Incorporated
2300 Dulles Station Blvd, Suite 650
Herndon, Virginia 20171

1. INTRODUCTION

Tensile testing is an important and standard method of measuring material properties for subsequent use in the design and analysis process. One key material property that is often determined using tensile testing is the elastic (Young's) modulus, which is a fundamental material characteristic describing elastic stiffness. It can be measured from the slope of the initial linear region of the stress-strain curve (see the generic curve in Figure 1.1). For stiff materials in particular, valid, and accurate characterization of the elastic modulus requires measurement of low strain levels with high accuracy and precision. Therefore, the strain measurement method needs to be chosen and implemented carefully to get reliable results.

This paper presents the basic setup and use of a number of different strain measurement methods to experimentally determine the elastic modulus of a common 3D-printing plastic material and discusses benefits and drawbacks of each method.

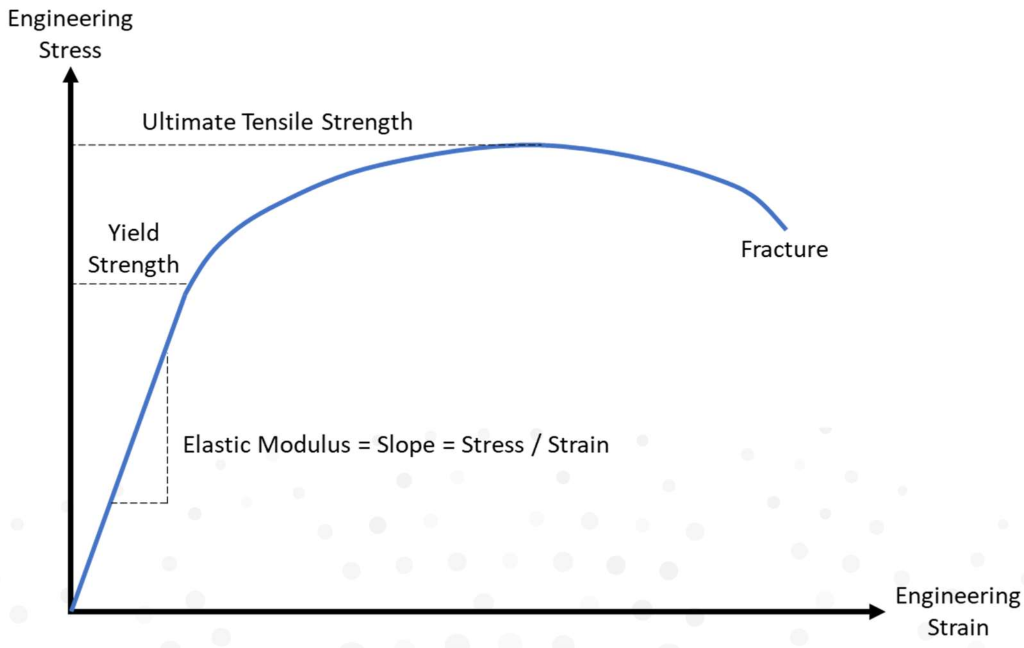

Figure 1.1: Example engineering stress-strain curve.

2. EXPERIMENTAL PROCEDURE

Dogbone specimens were 3D-printed in polylactic acid (PLA) and tested according to ASTM D638-22[1] and ASTM E111-17[2] using an Instron 34TM-50 universal testing machine (UTM). The Type II specimen dimensions were utilized and are depicted in Figure 2.1. The samples were pulled in tension until fracture at a speed of 5 mm/min, which corresponds to a nominal strain rate at the start of the test of 0.002 1/s. This low-rate loading results in measurements of the quasi-static modulus. This is in contrast to the dynamic modulus that manifests in plastics (polymers) due to their viscoelasticity, which is beyond the scope of this study. For all samples, the load was recorded using the UTM's load cell, and the engineering stress was calculated from the measured load by dividing it by the initial cross-sectional gauge area.

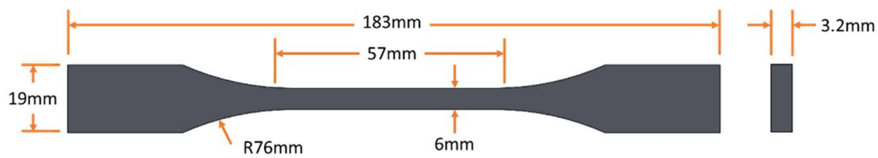

Figure 2.1: ASTM D638-22 Type II specimen shape and dimensions.

2.1. Strain Measurement Methods

Five different methods were used to measure the strain: the crosshead displacement, the crosshead displacement with machine compliance correction (MCC), a touch extensometer, a video extensometer, and a stereo digital image correlation (DIC) system. While other strain measurement methods exist, e.g. laser extensometers, strain gauges, etc., this paper focuses on the aforementioned five as they span a broad range of accuracy, ease of use, and cost considerations. Note that ASTM D638-22 and E111-17 recommend against computing elastic modulus from strain measurements based on crosshead displacement data. This paper purposefully does so anyway to show the consequences if this guidance is disregarded.

2.1.1. Crosshead Displacement

Utilizing the displacement of the crosshead, the moving part of the UTM where the load cell is mounted, is the simplest method. This is because it requires no other measurement instruments aside from what the UTM itself provides. Here, the strain is obtained by dividing the measured displacement by the nominal (initial) specimen length between machine grips. The simplicity of this method comes at a cost though: it is the lowest precision and most indirect measurement method, often resulting in erroneous strains as is discussed next.

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[1] *Standard Test Method for Tensile Properties of Plastics*, ASTM D638-22, 2022.
[2] *Standard Test Method for Young's Modulus, Tangent Modulus, and Chord Modulus*, ASTM E111-17, 2017.

2.1.2. Crosshead Displacement with MCC

One reason for the inaccuracy of strains derived directly from the crosshead displacement is the fact that the UTM itself deforms slightly during testing. This deformation can be due to the elasticity of the machine components as well as compliance within the load train and UTM mechanism. The net effect of these factors is referred to as machine compliance. Consequently, the crosshead displacement includes unwanted contributions of machine compliance that, if unaccounted for, result in overestimation of the true specimen strain. The effects of machine compliance are most pronounced for stiff samples, for instance, metal samples with high elastic moduli and large cross sections. To correct for machine compliance in tensile tests, it must first be measured experimentally. To do so, a relatively stiff sample (in this case, a steel bar with a cross section much larger than the plastic samples) is loaded in the UTM with the exact same grips, inserts, load cell, etc. as is used on the actual samples of interest. The resulting force-displacement data from this test characterizes the machine compliance. Once known, it can be used to correct the UTM crosshead displacement data, thereby obtaining the true sample displacement. This corrected displacement data is then divided by the nominal gauge length to obtain a more accurate measurement of the engineering strain of the sample.

2.1.3. Touch Extensometer

A touch extensometer is a separate instrument that attaches directly to the sample in the gauge region. In this way, the touch extensometer avoids the pitfalls of using the crosshead displacement by measuring the displacement of the sample directly. It measures the displacement between its two contact points relative to a smaller, more precise gauge length. This leads to more accurate measurements of sample strain with higher sensitivity and precision. Figure 2.2 shows the touch extensometer setup used herein.

Figure 2.2: Dogbone sample with touch extensometer attached.

2.1.4. Video Extensometer

Conceptually, a video extensometer operates largely in the same way as a touch extensometer. The main difference being it is a non-contact technique, which measures the sample displacement optically using a camera instead of a surface-mounted device. A telecentric lensFigure 2.3 was used to reduce the effects of out-of-plane motion on the strain measurement here. The setup for this strain measurement method is shown in Figure 2.3

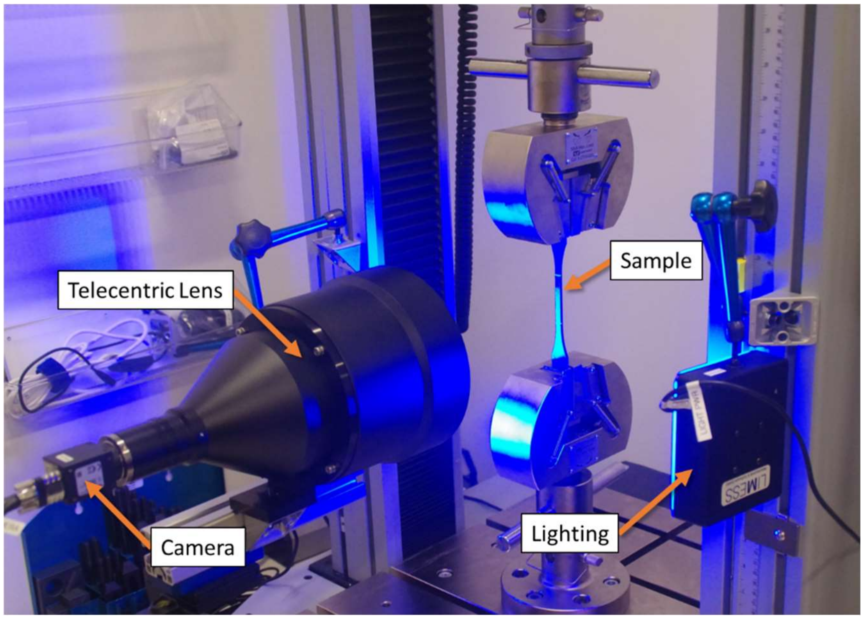

Figure 2.3: Video extensometer test setup.

Gauge lines (fiducials) on the sample, shown in Figure 2.4, are required for the image-processing software to track of the length of the gauge area during testing. These lines can be painted on the sample, drawn on with pencils or markers, or can be stickers made specifically for video extensometers. This last approach was used here. Regardless of method, the main requirement of the gauge lines is a large difference in reflected light across the line, providing the contrast necessary for the image processing software to track line positions. This was accomplished by having a white line next to a black line as is common practice. Lights are directed at the sample to increase this intensity difference, as seen in Figure 2.3. The straighter and sharper the lines, the less noise and higher accuracy one can achieve. Image processing of the gauge lines and the resulting light intensity diagram from the video extensometer software are shown in Figure 2.5.

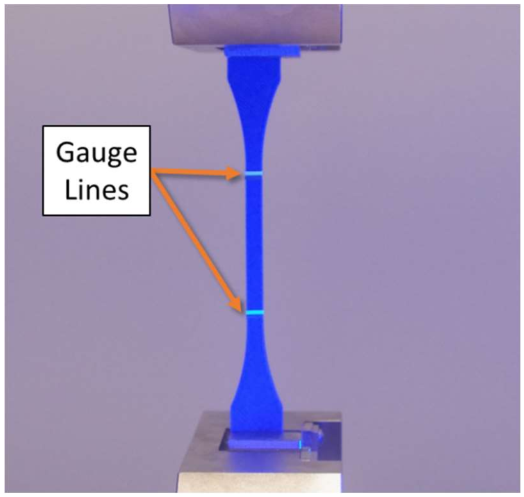

Figure 2.4: Sample with gauge lines used by video extensometer software to track sample displacement.

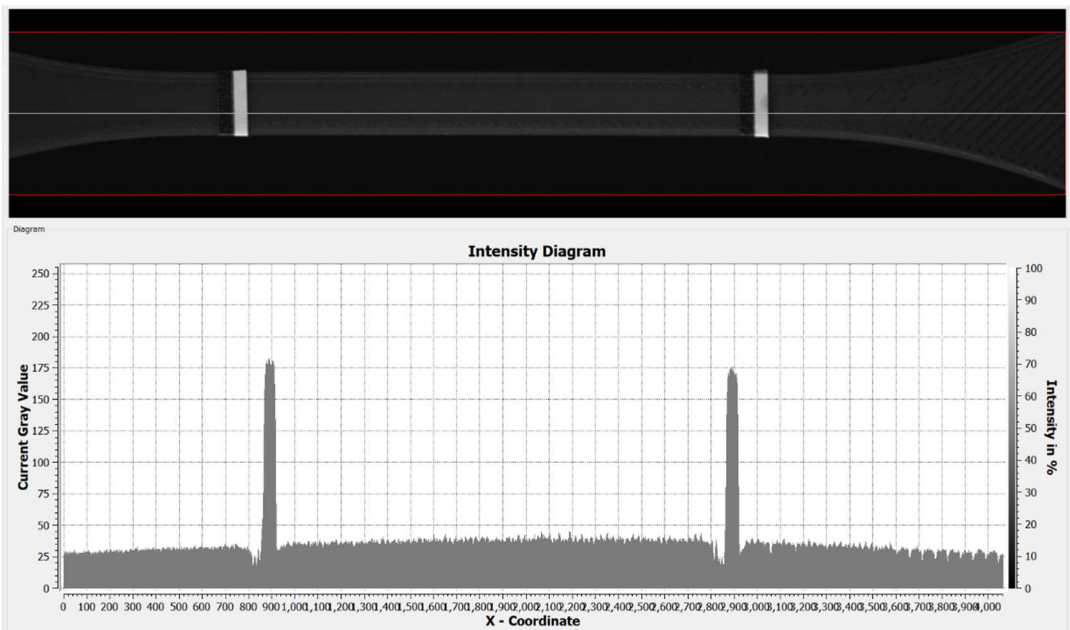

Figure 2.5: Video extensometer software showing camera image (top) & light intensity diagram (bottom). Peaks of intensity diagram correspond to gauge lines shown in top image.

2.1.5. Digital Image Correlation

Digital image correlation (DIC) is a non-contact, full-field strain measurement method. While the other methods only provide a measure of the average strain of a gauge section in at most two orthogonal directions, axial or lateral, DIC affords the user measurement of the local strain tensor field across the sample field of view. With a stereo camera system (i.e. two or more cameras), one can measure 3-dimensional displacements and surface strains of complex, 3-dimensional geometries.

Similarly to video extensometers, physical markings on the sample are required for the DIC image-processing software to track sample deformations; these markings are known as speckle patterns. The speckle pattern for the sample tested here using DIC is shown in Figure 2.6. There are many methods to speckle a sample (stencils, spray painting, airbrushing, stamping, stickers, etc.), and the choice of which to use is often sample- and test-objective-specific. Aspects of the speckle pattern, such as speckle size and spacing, directly affect the accuracy and resolution of the final strain measurement data.

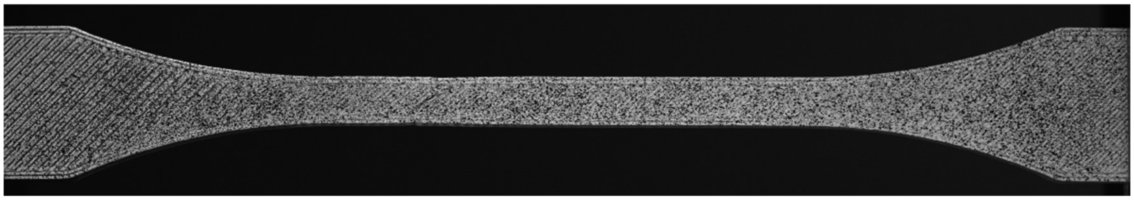

Figure 2.6: Sample speckle pattern used by DIC software to track deformations.

In addition to speckling the samples, there are numerous other setup tasks that must be performed prior to testing, such as determining and setting the camera distance, stereo angle, and distance-to-object; setting up the lighting; choosing and focusing the lens; and calibrating the system, which must be redone for even the slightest change in the cameras' positions or orientations. All of these tasks play a role in the accuracy and sensitivity of the ultimate DIC measurements obtained. The finalized test setup used herein is shown in Figure 2.7.

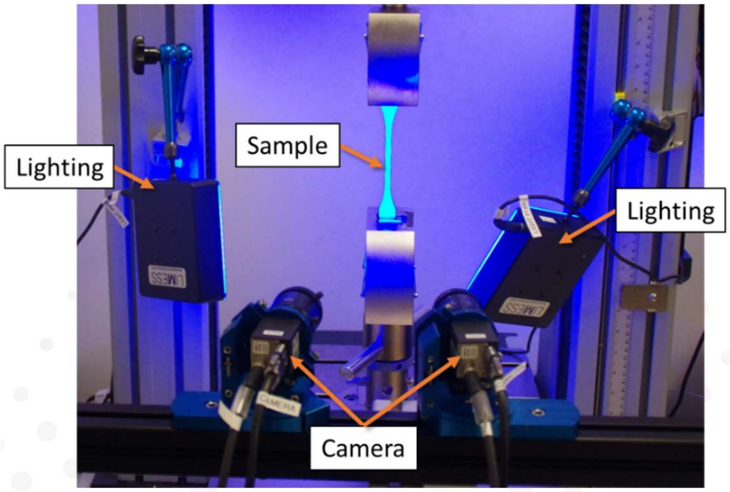

Figure 2.7: DIC test setup.

Once the test is complete, raw images are post-processed into full-field displacement and strain data which can then produce contour plots, make other specific outputs, etc. An important aspect of post-processing is choosing the associated parameters; the quality of results is highly dependent on the processing parameter values, and the optimal values are test- and output-of-interest-dependent.

3. RESULTS

The full engineering stress-strain curves generated from each of the strain measurement methods are shown in Figure 3.1. Figure 3.1 also highlights the linear elastic region used to calculate the elastic moduli in a separate plot. Though unrelated to elastic modulus measurement, one my wonder why the large strain curves from the touch and video extensometer samples show lower fracture strain than the other methods. This is simply due to specimen breakage outside of the gauge area for these individual tests rather than anything to do with the strain measurement technique used.

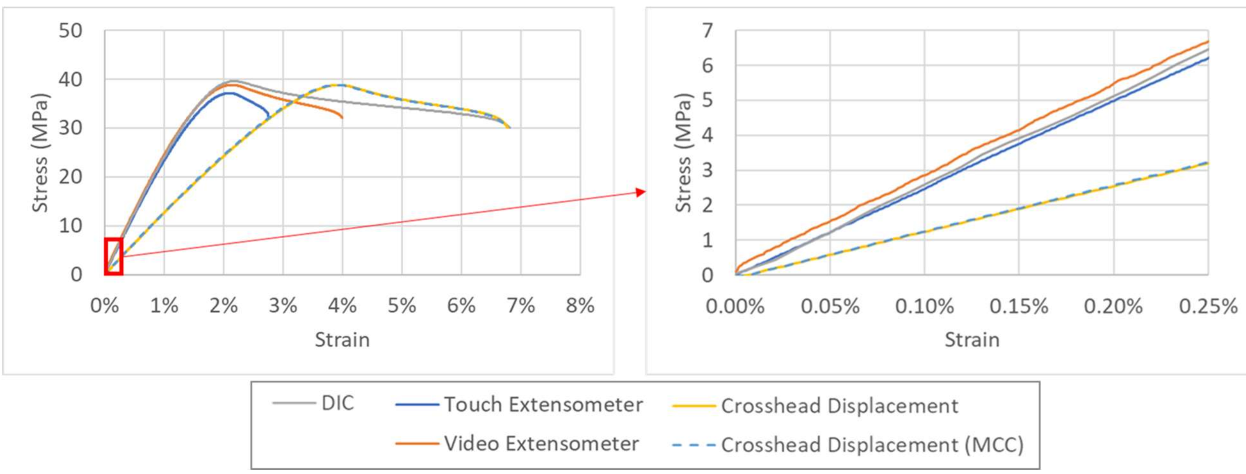

Figure 3.1: Engineering stress-strain curves obtained using various strain measurement methods.

For all strain measurement methods, the elastic modulus was determined by fitting the data in the 0-0.25% strain range with a linear line as per E111-17. Modulus values obtained from these fits are shown in Table 3.1.

Table 3.1: Experimentally Derived Elastic Moduli

Strain Measurement Method	Elastic Modulus (GPa)
Touch Extensometer	2.50 ± 0.10
Video Extensometer	2.62 ± 0.02
DIC	2.60 ± 0.01
Crosshead Displacement	1.31 ± 0.52
Crosshead Displacement (MCC)	1.33 ± 0.53
Material Datasheet[3]	2.64 ± 0.33

[3] *Raise3D Premium PLA Technical Data Sheet*, Version 4.0, 2019.

Error bounds shown are uncertainties propagated solely from the strain measurement resolution associated with each method. Additional uncertainties related to other measured variables (e.g. force or specimen dimensions) and errors of random and systematic type were neglected here to isolate the effect of strain measurement accuracy. Table 3.1 also includes the elastic modulus value given in the PLA filament datasheet from the material vendor for refence.

4. DISCUSSION

One can see the inaccuracy in the elastic modulus measured using the crosshead displacement alone directly from viewing the stress-strain curve. Interestingly, removing the effects of machine compliance did not affect the results significantly. This is likely due to the relatively low stiffness of the samples compared to the UTM. One might wonder, if machine compliance is not the root cause of the inaccurate crosshead-derived strains, then what is? The main cause is that crosshead displacement takes into account the length-change of the entire sample, not just the gauge area. Looking at Figure 2.1, one can see that the transition areas between the gauge and grip sections are quite long. These areas will deform less than the gauge area due to their gradually increasing width, but that amount of deformation is non-negligible. This is a good example showing that while machine compliance correction can improve the accuracy of crosshead-derived strains, there are other sources of inaccuracy that can outweigh it. Additionally, it illustrates why methods that directly measure the displacement of the gauge area are almost always a more accurate and reliable choice. These reasons are why ASTM D638-22 and E111-17 recommended against utilizing crosshead displacement data in this application.

Elastic modulus values derived from touch extensometer, video extensometer, and DIC are all in good agreement with the value pulled from the material datasheet. This example test data clearly shows that each of these are reliable methods to accurately measure the strain and thus the elastic modulus in a tensile test. Then, how does one choose between them? The choice often comes down to ease of use, time, cost, and technical requirements. While a touch extensometer is often the cheapest of the three options, its limits are easily reached. For instance, many touch extensometers have a limited strain range they can measure and need to be removed once that range is exceeded. This can increase the test time per sample when going right into full stress-strain curve characterization or when using a thermal chamber. Additionally, attaching touch extensometers to very small samples, thin samples, or samples with certain surface finishes can be difficult and influence the mechanical response of the samples and/or the accuracy of the strain measurements. These problems can often be resolved through the use of specialized touch extensometers, but purchasing and maintaining multiple devices can be costly.

Non-contact methods, such as video extensometers and DIC, circumvent all these limitations and, when implemented properly, produce the highest accuracy strain measurements. However, these methods come with their own disadvantages. For instance, line-of-sight must be maintained, changes in lighting during testing can adversely affect measurements, and debonding of the gauge lines or speckle pattern can invalidate the results. Another potential disadvantage is cost: the initial cost of cameras, lens, stands, lights, software, etc. can be substantially more than the previously discussed methods depending on quality. Additionally, as was illustrated in Section 2.1.5, the amount of pre- and post-processing required per sample for DIC is quite large and time-consuming, and the rich amount of data that is produced may be underutilized in a basic dogbone tensile test. Although the effort involved with DIC is relatively high, its capabilities far surpass those of the other four methods and is better suited for more complex geometries (e.g., fillets, holes, and non-planar surfaces) and tests studying more complicated mechanical behavior (e.g., 3D deformations and crack propagation). Video extensometers, on the other hand, strike a good balance between accuracy and ease of use for most simple tests as in the case studied here. In many cases, the setup time per sample is equal to or less than that when using a touch extensometer.

5. CONCLUSIONS

This paper has shown the importance of selecting an appropriate strain measurement method when extracting material properties from dogbone tensile tests, specifically in terms of elastic modulus here. While using the crosshead displacement is cheap and easy, it often leads to inaccurate strain data (with or without using machine compliance correction). This results in misleading or inaccurate modulus values. Touch extensometers are often the next cheapest option and can produce accurate results, though their use is not entirely without difficulties. Specifically, they can be finicky to use, especially with small, slippery, or flimsy samples, and can be limited to narrow strain ranges. Out of the non-contact methods considered here, video extensometers are the preferred choice over DIC for simple dogbone tensile tests due the optimal combination of easy setup, real-time data processing, high accuracy, and lower costs. As the test complexity increases or as technical needs demand, the capabilities of video extensometers can quickly be exceeded, necessitating the full-field strain measurement capability provided only by DIC methods.

This simple example showcases a few of the many pitfalls and nuances associated with mechanical testing and the need for experience and careful consideration when designing and conducting tests to extract accurate and meaningful measurements. Quartus Engineering approaches test planning and execution with the understanding of the fundamental physics and that high-quality data is critical to support the creation of highly engineered solutions. Our objective is not only to deliver on this, but also to strive to maximize the value proposition for our customers.