# AER 304: Tensile Testing of Materials

University of Toronto Institute for Aerospace Studies

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## 1. Purpose

There are three goals to this laboratory. First, the experiments are intended to illustrate some of the different behaviours of common materials that are used in aerospace when they are loaded in direct tension beyond their strength. During the course of this experiment, observe carefully the differences in macroscopic behaviour between the various material specimens. Second, the experiments demonstrate the accuracy of the usual continuum theories of solid mechanics in practise. When analyzing the data you collect, make particular note of behaviour that is inconsistent with what we assume in a continuum theory. Third, the laboratory illustrates some of the most common experimental procedures and data acquisition tools used in structures and materials laboratories.

## 2. Safety Considerations

This is an active research laboratory. Several fundamental safety precautions must be followed:

- There are many heavy objects that may accidentally be dropped. Reasonably sturdy closed footwear is a necessity. No flip-flops or open-toed shoes.
- Loose clothing and unconstrained long hair are hazardous. The servo-hydraulic MTS load frame is capable of displacement rates up to 100 m/s. If something loose gets caught in the machine, very serious injuries may ensue.
- Safety goggles must be worn while experiments are in progress.
- No mobile telephones are permitted in the laboratory: if you are looking at your phone you are not paying attention to the equipment.

### 3. Apparatus

- MTS 100 kN servo-hydraulic load frame; wedge tensile grips
- National Instruments LabView data acquisition system
- laser extensometer
- VIC-Snap image acquisition hardware and software
- Ncorr digital image correlation software

### 4. Experimental Setup

Five dogbone tensile specimens made of various materials will be provided; see figure 1 for their nominal dimensions. These specimens are designed to be similar to but smaller than the specimens described in ASTM standard E8/E8M-13a. The purpose of the dogbone shape is to reduce the stress in the grip sections relative to the stress in the gauge section. A serious difficulty in tensile testing arises because failure can occur at the grips rather than in the gauge. Also, at the grips the stress is not uniform, while to extract useful information from the test it is necessary to have a region of uniform stress. Saint-Venant's principle tells us that the stress in the gauge section a short distance away from the grip section should be essentially constant.

After machining to the correct dimensions, the specimens are further prepared by adhering a two-axis strain gauge (TML FCA-5-11-3L two-axis gauge characteristics: 120 Ω, gauge factor 2.11) to the specimen surface at the centre of the gauge length. A random black and white speckle pattern is applied to the opposite side of the specimen covering the full extent of the gauge length. Two pieces of reflective tape are also bonded to one edge of the specimen within the gauge length.

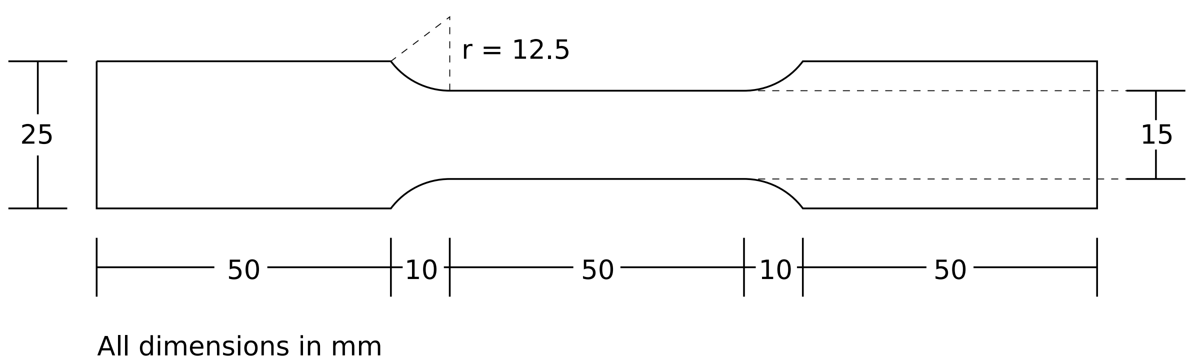


Figure 1: Plan view of the dogbone shape of the tensile specimens.

The 100 kN MTS servo-hydraulic load frame is configured with wedge tensile grips. These grips hold the specimens through shear tractions applied through the surfaces of the grips to the grip regions of the specimens and, as the total tensile force on the specimen increases, the gripping force provided simultaneously increases. The MTS is controlled through a computer interface; the user sets the various test parameters. In this experiment, the only necessary parameter is the cross-head displacement rate.

In general, experimental data are acquired using transducers which generate analog electrical signals. These signals typically have to be converted to voltages (usually between -10 and 10 V) to be correctly interpreted by most data acquisition systems. In some cases, transducers producing digital signals are also available, but will not be used in this experiment. Data will be acquired from three sources:

1. strain gauges adhered to the specimen;
2. a laser extensometer; and
3. digital photography.

The strain gauge is connected to a signal processing circuit consisting of a quarter Wheatstone bridge to amplify the change in resistance of the strain gauge as a consequence of straining and provide voltage output. The laser extensometer uses reflected laser light to measure the displacement between two pieces of reflective tape; the unit provides voltage output which is directly read by the data acquisition hardware. A digital camera will also be employed to collect high-resolution optical images of the specimen during the tensile test.

## 5. Experimental Procedure

Before beginning any of the loading procedures, examine each specimen carefully. **Measure the specimen dimensions** to ensure that they are consistent with the nominal dimensions shown in figure 1 and record the measurements.

The experimental procedure for all of the specimens will be identical. Before the test begins, the data acquisition equipment will be zeroed and a set of reference images of the specimen will be collected. The MTS load frame will displace the grip sections of the specimen with a varying cross head speed determined by the TA depending upon the material (to be recorded during the test). Load, displacement, strain and time data will be collected once per second by the LabView system. Shortly after the beginning of the test, when the specimen has experienced approximately 0.05% strain, the displacement direction will be reversed and the load will be relaxed. This is a more reliable method of measuring Young's modulus than during loading because in the unloading phase only elastic behaviour occurs. The unloading region in the resulting load-displacement relation is the best data set from which to extract Young's modulus. During the test, digital photographs of the specimen will periodically be collected. **Be sure to bring a high-capacity USB stick to collect the images after the completion of the testing.** These images will be collected automatically at a predetermined rate, and additional images may be collected as desired. The test will proceed until the specimen breaks or the test is discontinued for other reasons.

### 6. Data Acquisition

For each experimental specimen, there will be two sets of data acquired:

1. a LabView data file containing load, displacement, strain and time data; and
2. a set of images of the specimen at various times during the test.

The LabView data files will be formatted such that data from each individual measurement is in a single column.

### 7. Material Behaviour

The primary goal of this experiment is to observe differences in the ways in which common materials behave when subjected to direct tensile loads. A non-exhaustive list of things to observe is:

- the elastic properties of the material: Young's modulus and Poisson's ratio;
- the post-elastic response: yielding, fracture;
- any non-continuum effects that arise: strain localization.

### 8. Analysis of Strain

The image analysis will be completed using the Ncorr digital image correlation package (for more information, see www.ncorr.com) that runs in a Matlab environment. Ncorr has been installed on several computers in the Engineering Computing Facility, but can also be downloaded and installed on a personal computer. The principle behind digital image correlation is that two images of the same specimen, taken under different conditions, can be compared at a very fine scale to measure some changing physical characteristic of the specimen. In this experiment, we are interested in the deformations exhibited by a random black and white speckle pattern on the surface of the specimen. Note that this requires the assumption that surface information is an acceptable representation of a phenomenon that extends through the volume of the specimen.

Detailed instructions for Ncorr are available from the Ncorr web site. Here a brief description of the process will be provided. Use a Linux machine either in the lab or remotely. First, launch a command window. Second, the Ncorr Matlab directory must be linked to your home directory. Use the command:

```
ln -s /share/copy/aer304/NCORR NCORR
```

This creates a symbolic link to the Ncorr directory in your home directory. To launch Ncorr, change to the NCORR directory you just created and launch Matlab. Type

```
handles_ncorr=ncorr
```

at a Matlab prompt. This will spawn a graphic user interface. All subsequent actions are taken using the GUI. The overall process for strain mapping is:

1. Select the base image to which you wish to compare all the other images. This will be one of the images that were captured before the beginning of the loading.
2. Select the images for which you wish to calculate strain maps.
3. Define the region of interest (ROI) for the strain calculation. This should in general be the full extent of the gauge length.
4. Define the correlation parameters. The defaults are typically adequate.
5. Choose the region of interest for which you wish to perform the calculation (useful only if you have selected more than one ROI and do not wish to map all of them).
6. Launch the analysis.

Once the analysis is complete, the estimated displacement of each point in the analysis region has been calculated. These displacements can be converted into the various components of strain through relations such as those studied in AER 373; this involves calculating the numerical spatial derivatives of displacement and can be done by selecting options in Ncorr.

For the purposes of the laboratory, the key information that can be obtained from the digital image correlation is the evolution of the strain field in the gauge length. These strain fields can be compared with the measurements taken using the strain gauge and the laser extensometer. In all cases, the measured strain is an average over some length or radius. In the case of the strain gauge, it is an average over the strain gauge length. For the laser extensometer, it is an average over the distance between the laser tapes. For the digital image correlation, the averaging length depends upon the parameters chosen for the calculation. The Ncorr manual provides an excellent description of the relevant correlation parameters. It is helpful to experiment with these parameters to gain a better understanding of what is happening during the calculation.

## 9. Laboratory Report

For all of the specimens, calculate the following quantities: Young's modulus, Poisson's ratio, yield stress (using 0.2% offset strain; see appendix A) and ultimate tensile stress. For the Young's modulus, calculate it using strain data from the strain gauges, the laser extensometer and the digital image correlation. Compare the results you get from each of the calculations. Examine a series of strain maps generated using digital image correlation. In particular, identify conditions where our fundamental assumptions of continuum behaviour break down and instead we see stain localization. In some strain maps, you will see regions where strain is localized rather than constant. Provide some ideas about what might be happening in these cases.

The due date for the laboratory report is one week after the laboratory session. It should be submitted electronically though Quercus. **Please limit the size of the file upload to 20 MB.**

## A. Offset Strain

For many metals (steel is an unusual exception) there is no well-defined yield point. Instead, the stress-strain curve looks like that shown in figure 2. To overcome this lack of clear definition, a common approach is to define the yield stress as the stress at which the material has 0.2% offset from linear behaviour. The modulus of the material is defined by the linear part of the stress-strain curve that begins at initial loading. A line parallel to the initial loading curve (that is, with slope equal to the Young's modulus) is drawn starting at strain $\epsilon = 0.2\%$. The level of stress at which this line crosses the actual stress-strain curve is taken to be the yield stress of the material.

## B. Report Format

The following sections should appear in your lab report. A brief description of the material to be in each section is also included.

1. Introduction
   - purpose of the lab and some background (paraphrasing, not copying, the lab manual)
2. Experimental Apparatus
   - give details of the equipment used, including model numbers if available
   - if you include photographs of the equipment, ensure that they are not blurry

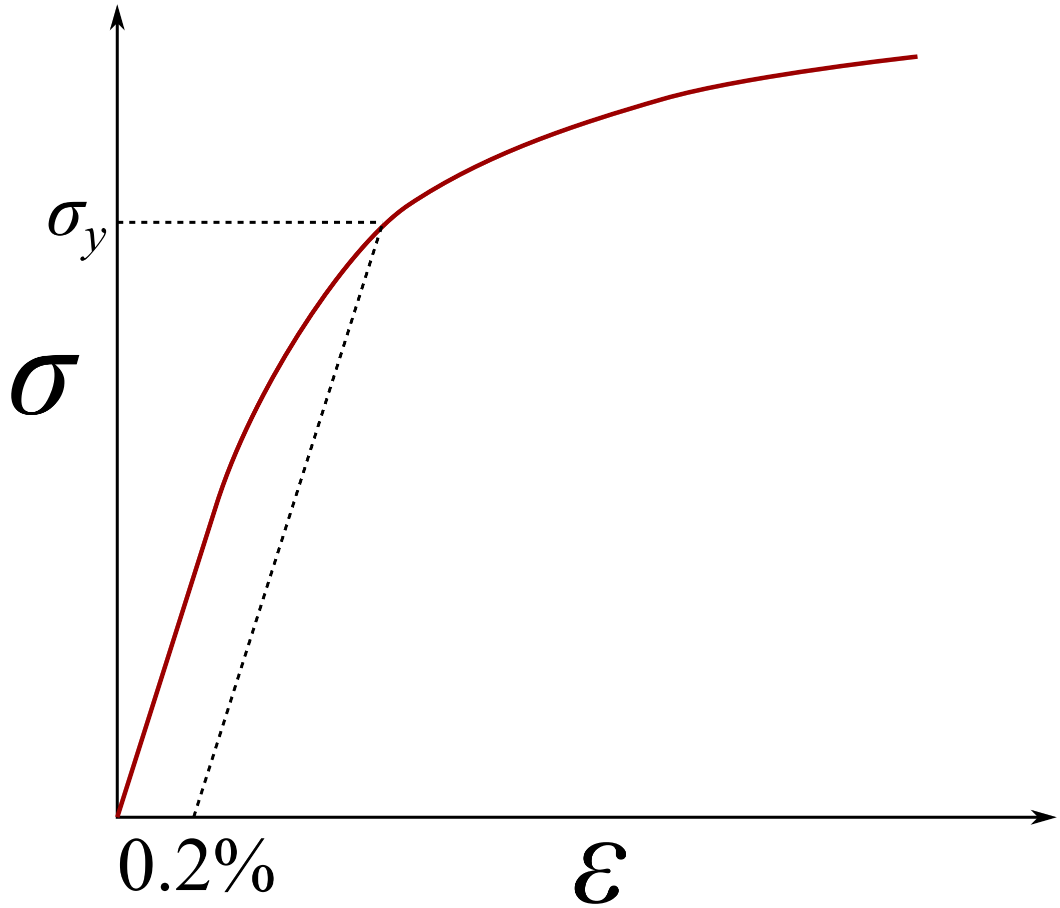


Figure 2: Stress-strain relation for a typical metal.

3. Procedure
    - describe the procedure with reference to the lab manual, explaining any variations from the intended procedure
    - provide the measurements of the specimens
4. Experimental Results
    - the processed data arising from the experiments, in tabular or graphical form
    - Ncorr images, at least one from each specimen; consider carefully which images are most illustrative of the interesting phenomena that you observed
    - do not comment on the results; merely present the data

5. Sample Calculations

   - for every calculation that you perform, you should provide one sample calculation; for example, if you calculate Young's modulus, provide a sample of how you have done so
   - do not forget units

6. Discussion

   - comment on the overall behaviour of the specimens: ductile / brittle etc.
   - comment on discrepancies between actual behaviour and theory, and provide explanations for the discrepancies
   - identify the materials that you tested, including the alloy designation and an indication of what evidence you used to make this determination

7. Sources of Error

   - qualitatively identify sources of error in your results
   - explain how this would affect the results

8. Conclusions

   - summarize the main findings of the lab
   - if you claim that your results match or do not match the theory, explain why this is the case with reference to your results and discussion
   - recap the purpose of the lab and its objectives; were the objectives met?
   - do not provide new information in the conclusions; this should have been presented in the results and discussion

## C. Report Style

The following is a non-exhaustive list of style points that should be followed for the AER 304 lab reports.

1. General Style

   (a) do not copy text directly from the lab manual; always paraphrase

   (b) descriptions of procedures should be in past tense as they have already been completed

   (c) keep your units consistent: modulus in GPa, stress in MPa, displacement in mm, forces in N or kN
   (d) figures are figures and tables are tables; they should be numbered separately

2. Graphs and Figures
   (a) all graphs, figures and tables must be high quality graphics (no screen shots), and must be accompanied by a descriptive caption
   (b) when graphing forces and displacement, all graphs should start at zero; if your data do not start at zero, apply an appropriate offset
   (c) separate data meaningfully; do not put too much onto a single graph or figure
   (d) do not include long tables of raw data; unless you think someone should read a particular number, do not include it in your report
   (e) put units on both axes of graphs
   (f) in general, graph force or stress as a function of displacement or strain; time should never be one of the axes