University of Washington

ME 354
Laboratory Manual

Torsion Testing
Lab Write-up

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The torsion test is of great utility for determining the flow stress at high strains. It has, for example, wide application at elevated temperatures for the estimation of rolling loads because of its ability to impart the high accumulated strains of 4 or 5 induced during commercial rolling.

- G.R. Canova (1982)[1]

1 Overview

In this lab, students will study the shear response of two different metals, 6061-T6 aluminum and A36 steel, via torsion experiments on long slender rod specimens. A torsion testing setup in MEB 127 will be used to apply torsion to the rods until the onset of failure. Load and rotation data will be recorded manually and excel data for the test will be provided via Canvas. Through this lab, students will learn about fitting plasticity constitutive equations (particularly power-law hardening), the experimental application of pure shear and the elastic-plastic behavior of a shaft under torsion.

2 Background

A torsion test is a relatively straightforward method for applying a state of pure shear to a material. Torsion does not cause necking in a specimen, making it easier to study stress-strain relationships through the full testing range up to failure. The results of the test (torque vs shearing angle) very closely resemble the uniaxial stress-strain relationship from a tension test. However, the state of stress that develops during a torsion test is non-uniform throughout the specimen cross-section, meaning that although the results may look familiar, a certain degree of care must be taken in analyzing them.

2.1 Sample Preparation

Torsion specimens are generally long, slender rods. They must be sufficiently slender such that a torque can be applied to them without the grips at the end affecting the state of stress in the middle of the specimens. They generally have a uniform diameter along their length, although they can have a splined or hex cut grip region to aid in the application of torque. It is important to ensure that the prepared rod specimen is perfectly straight, as any pre-test bend in the specimens may lead to premature failure.

Fabrication of the specimens can be done using any machining method that ensures a uniform cross section throughout the gauge length. The most common method for fabricating long uniform members is extrusion molding (where material is pushed through a die) or pultrusion (where material is pulled through a die). It is important, however, to consider the microstructural changes that can occur during such a process, and alternate fabrication methods or post-extrusion heat treatment may be needed if a particular microstructure is desired.

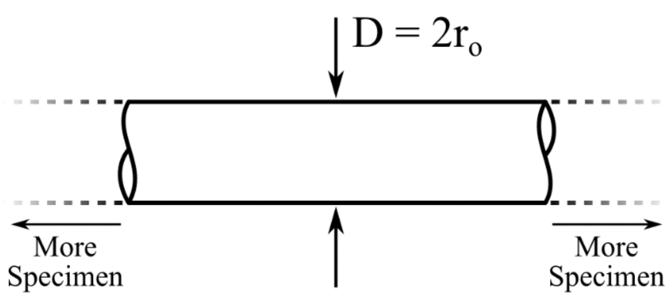

***Figure 1**: Schematic of a torsion rod specimen.*

2.2 Stress, Strain and Constitutive Relationships

The shear stress (τ) and shear strain (γ) in a torqued rod are proportional to the applied torque (T) and twist angle (θ) respectively. They are non-uniform throughout the cross-section of the rod, but they can be assumed to vary linearly along the radius while the rod is still in the elastic region. Here, the relationship between the torque and shear stress can be defined as

$$\tau = \frac{Tr}{J} \quad , \tag{2.1}$$

where J is the polar moment of inertia (or second moment of area) and is $J = \pi r_o^4/2$ for a solid circular rod, with r_o being the radius of the rod. The shear strain can be defined as

$$\gamma = \frac{\theta r}{L} \quad . \tag{2.2}$$

The maximum shear stress and shear strain are found at the outer radius r_o. In the elastic stress region, the shear stress and shear strain are related to each other by the shear modulus (G) as

$$\tau = G\gamma \quad , \tag{2.3}$$

which can be determined from the slope of the shear stress vs shear strain data. The relationship between torque and twist angle in the rod in the elastic regime can then be defined as

$$T = \frac{\tau J}{r} = \frac{G\gamma J}{r} = \boxed{\frac{G\theta J}{L} = \frac{\pi r_o^4 G\theta}{2L}} \quad . \tag{2.4}$$

Once the maximum shear stress passes the yield limit of the material, the rod will begin to deform plastically starting at the outer surface of the sample and continuing to the plastic radius (r_y), defined as

$$r_y = \frac{\gamma_y L}{\theta} = \frac{\tau_y L}{G\theta} \quad , \tag{2.5}$$

where τ_y is the shear yield strength. Inside this plastic radius r_y, the bar is still elastic, and outside of it, the stress can be found according to the plastic constitutive relationship for the material. This is illustrated in Fig. 2E. For the materials used in this lab, it can be assumed that the stress follows a power law hardening relationship with strain. This is represented by

$$\sigma = H\varepsilon^n \;\equiv\; \tau\sqrt{3} = H\left(\frac{\gamma}{\sqrt{3}}\right)^n \quad , \tag{2.6}$$

where H and n are coefficients that can be found by fitting to uniaxial stress-strain data. The relationship shown in Eq. 2.6 for shear stress and strain is obtained using equivalent stresses. The torque in the bar is now calculated as the sum of the torque in the elastic (T_{el}) and plastic (T_{pl}) region. These are found to be

$$T_{el} = \frac{\pi \tau_y r_y^3}{2} \quad , \tag{2.7}$$

$$T_{pl} = \frac{2\pi H}{\sqrt{3}(n+3)}\left(\frac{\theta}{\sqrt{3}L}\right)^n \left(r_o^{n+3} - r_y^{n+3}\right) \quad , \tag{2.8}$$

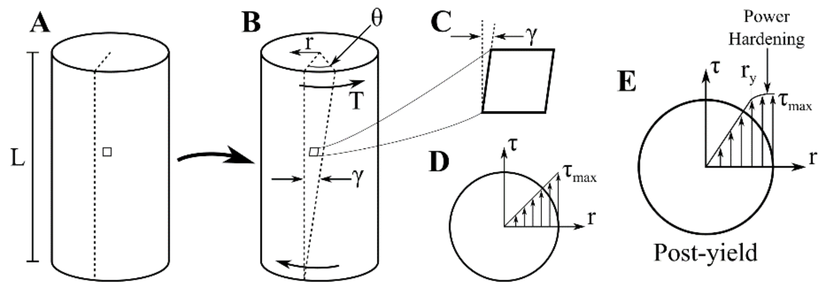

Figure 2: *Schematic of a tensile test illustrating the pure shear that develops in a specimen. A) initial specimen, B) sheared specimen, C) close up showing simple shear state on the surface, D) shear stress distribution prior to yielding and E) shear stress distribution after yielding.*

2.3 Material Properties

In this lab, you will be fitting exponential hardening plastic properties to your experimental torsion data. **You should use the elastic and yield properties for the A36 steel and 6061-T6 aluminum that you obtained in the tension lab**. Property values for H and n have been determined from the uniaxial tensile test in last week's lab. These values are provided here, but they can be calculated for extra credit, as is described in Section 5 below.

Table 1: *Plastic hardening properties for A36 Steel and 6061-T6 Aluminum.*

	$\boldsymbol{H(MPa)}$	$\boldsymbol{n}$
A36 Steel	779	0.194
6061-T6 Al	374	0.0417

The material constants in this table were obtained from fitting to plasticity data from tension lab. There is a variance in the properties here that we are not reporting, and part of this lab will be performing a sensitivity analysis to see how different values can affect the fit. It can be assumed that this variance is ±10%, or, if you perform your own fit to the tension data, you can use those results for the variance. If you believe there is an error in the table, just explain the discrepancy and discuss in the discussion section.

3 Experimental Setup and Procedure

3.1 Equipment

- Technovate torsion testing setup
- Troptometer (to measure angles)
- Digital load readout
- Constant diameter rods of 6061-T6 aluminum and 1018 steel

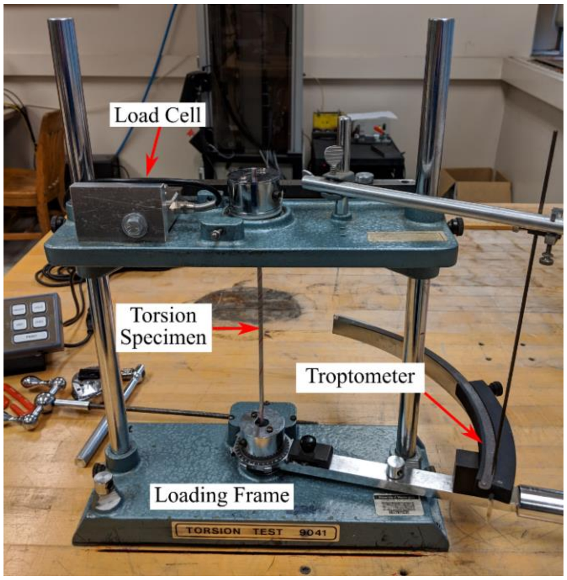

Figure 3*: Image of the testing setup.*

3.2 Setup

1. Measure the diameter of the specimen gage section using the calipers provided; record the measurement on the Torsion Data Sheet (provided at the end of the manual).
2. Perform the following steps under the close guidance of the lab instructor:
   a. Draw a longitudinal line on the specimen using the ink marker
   b. Install the bottom end of the torsion test specimen in the bottom grip of the test machine. Make sure the specimen is *very* tightly clamped in the bottom grip.
   c. Locate the pin behind the lower grip that engages the ratchet mechanism and make sure this pin is pulled forward (i.e., make sure the ratchet is engaged).
   d. Unthread the horizontal drive rod until the end of the threaded region has reached the threaded nut (i.e., until the end of the threaded rod is almost disconnected from the base). Then rotate the lever arm counter-clockwise (i.e., move the lever arm handle to the right) as far as possible.
   e. Inspect the top grip and identify the wire ropes that transfer torque to the top grip/specimen. Loosen the two nuts as far as possible.
   f. Rotate the top grip clockwise, so as to remove 'slack' in the wire ropes. While holding the grip in this position as firmly as possible, tighten the top grip of the test machine. Make sure the specimen is *very* tightly clamped in the top grip.
   g. While monitoring the force sensor, remove any remaining slack in the wire ropes by re- tightening the two nuts that were loosened during step (e). If the nuts are completely tightened and slack still remain, tighten the threaded horizontal drive rod until an increase in load is sensed.
   h. Measure and record the distance between grips. Notice that the bottom face of the upper jaw is recessed into the upper plate. Make sure to account for this recessed distance in your measurement.
   i. Adjust the pointer so as to indicate "zero" degrees.
   j. Zero the output of the force sensor.

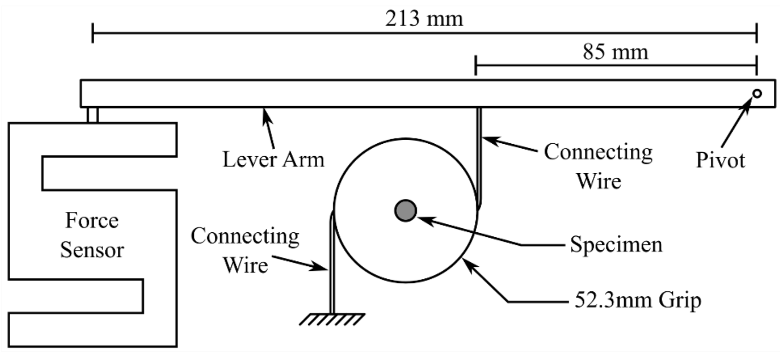

Figure 4*: Schematic of the torsion load measurement configuration.*

3.3 Procedure

1. Use the threaded drive rod to apply a known angle of twist to the lower grip. Increase the angle of twist as follows:
   a. Increase the angle of twist in increments of 2°, until a total angle of twist of 30° is reached and record the force displayed on the force gage at each increment.
   b. Next, increase the angle of twist in increments of 5°. Continue to make measurements in increments of 5° until the ratchet in the lower grip "clicks. This may occur at a total angle of twist of 45° but depending on the initial conditions imposed during steps (f) and (g) above, the ratchet may "click" at a total angle of twist near 50°, 55°, or 60°. Simply continue to take data in 5° until the "click" occurs.
   c. Record four measurements at increased angles of twist, in increments of 45°.
   d. Record four measurements at increased angles of twist, in increments of 90°.
   e. Record four measurements at increased angles of twist, in increments of 180°.
   f. Record measurements at increased angles of twist in increments of 360°, until specimen failure occurs (failure often occurs at about 7 full rotations, but depends on the grip-to-grip distance).
2. Remove the broken halves of the specimen after failure occurs.
3. Carefully examine the specimen and fracture surface. Record enough information (in the form of sketches and notes) so that the appearance of the specimen and fracture surface can later be described in your report.

4 Analysis and Report

This laboratory requires a lab write-up, which comprises the analysis and discussion of the results obtained during testing. It is intended to both gauge students understanding of the test method/analysis and their ability to concisely present and discuss the engineering test results. Please adhere to the guidelines set forth by the 'Write-up Sheet' document found on the course website. In this write up, students should:

- Plot the experimentally measured applied torque vs twist angle for each material.
- Plot the theoretical torque vs twist angle relationships assuming power law hardening materials. These can be superimposed on the experimental plots.
- Find the shear modulus (G) from the torque vs angle plot. This can be compared with the uniaxial data from the tension results as $G = E/2(1+\nu)$.
- Determine the plastic radius (r_y) for every applied twist angle.

- Determine the elastic and plastic components of the torque after the onset of yielding.
- Perform a sensitivity analysis on the power law hardening coefficients to determine how sensitive the theoretical prediction is to them.

The discussion should focus on:

- The difference between the experimental results and the theoretically predicted results using a power law hardening model for both materials
- The nature of the failure (i.e. what the failure surface looks like and what direction it is) along with what that suggests about the material itself.
- Any sources of error or noise in the results. Is the primary error due to instrumentation, methodology, error in the analysis, or something else?
- The sensitivity of the results to various input parameters.
- Anything surprising in the results.

Error analysis should be done using statistical methods (i.e. mean, standard deviation, R^2 for linear regressions, etc.), and bounds should be given for the properties obtained based on known uncertainties in the measurements. A data analysis guide for the lab will be provided on Canvas as a flowchart for student to conduct the data analysis with any preferred method/program.

5 Extra Credit Opportunity

Extra credit (up to 5% of the total grade) will be awarded if students determine the values of H and n for each material using a power hardening model fit to the tension data from the previous lab. Students must show their steps in getting H and n and discuss how this relates to their sensitivity analysis. The extra credit will be awarded by including the fit results in your report and submitting any code or analysis separately from this lab via Canvas.

6 References

[1] G.R. Canova, S. Shrivastava, J.J. Jonas, C. G'Sell, The Use of Torsion Testing to Assess Material Formability, Formability Met. Mater. AD. (1982) 189–210.

Data Sheet – Aluminum

Diameter:

Length (grip-to-grip):

Table 2: *Angles of rotation and force measured on aluminum*

Angle (deg)	Force (N)	Angle (deg)	Force (N)
0			
2			
4			
6			
8			
10			
12			
14			
16			
18			
20			
22			
24			
26			
28			
30			
35			
40			
45			

Data Sheet – Steel

Diameter:

Length (grip-to-grip):

Table 3: *Angles of rotation and force measured on steel*

Angle (deg)	Force (N)	Angle (deg)	Force (N)
0			
2			
4			
6			
8			
10			
12			
14			
16			
18			
20			
22			
24			
26			
28			
30			
35			
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