Structural Mechanics 2 Laboratories

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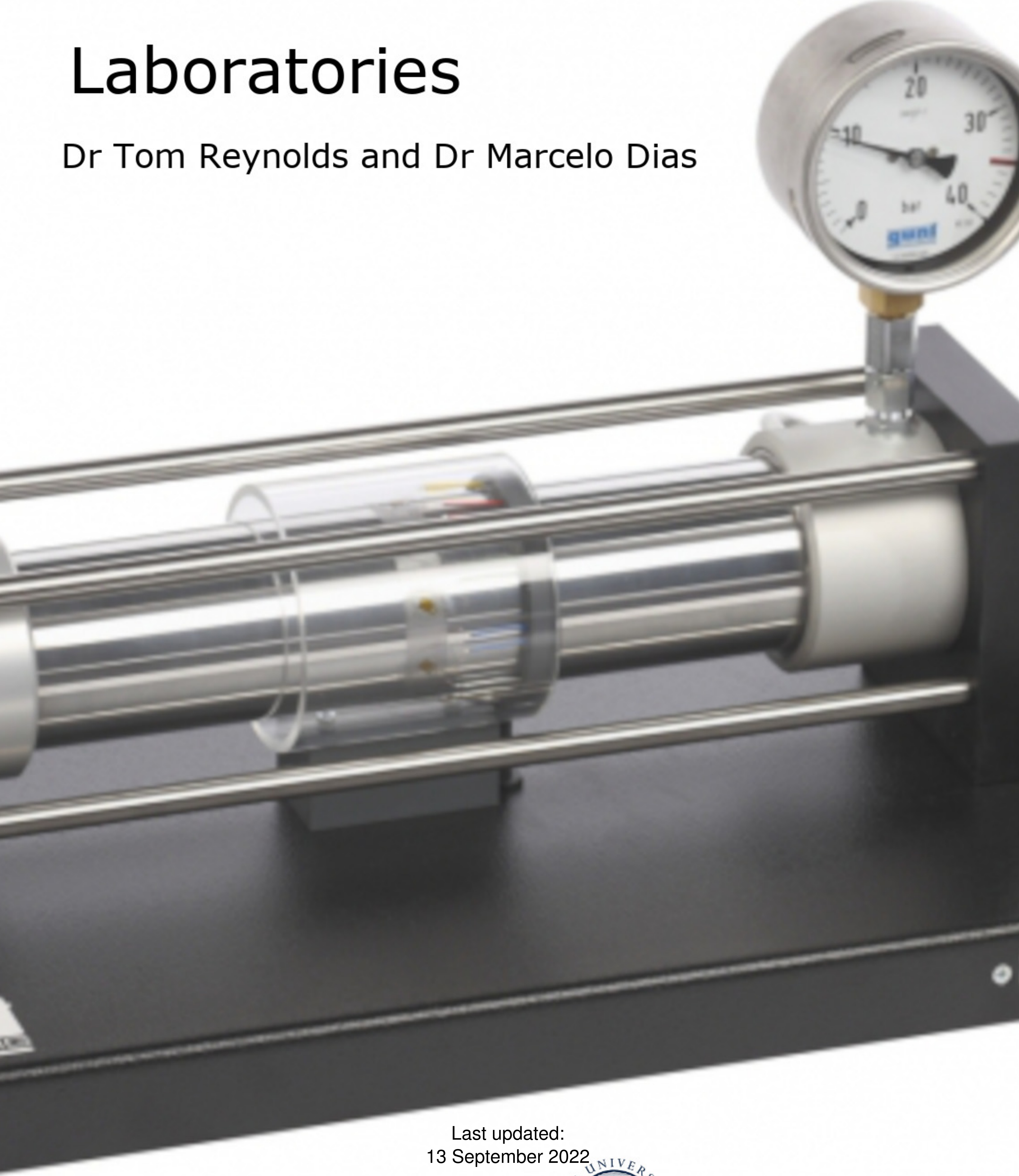

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THE UNIVERSITY *of* EDINBURGH
School of Engineering

Contents

1 Overview

There are four laboratory exercises to complete as part of Structural Mechanics 2:

1. Composite action in a beam
2. Torsion of a shaft
3. Membrane stresses in a pressure vessel
4. Load and stress in a truss

Each exercise has two parts: data collection and analysis. The data collection phase for exercises 1. to 3. take place in your timetabled physical laboratory session in the light structures lab, TLM. Exercise 4. is a remote laboratory, so you will collect your dataset online, controlling the truss structure remotely.

The analysis is carried out in your own independent study time. Discuss your work with other students in your cohort, but do not carry out the analysis together. You will write a single report containing these four exercises, and this will form your coursework for Structural Mechanics 2.

How to use these notes

These notes contain all the tasks you have to carry out, and all the questions you have to answer to complete your coursework, for submission at the end of semester 1. There is only one submission, but you will need to work on it throughout the semester.

The two parts of each exercise will require your attention at different times:

1. **Data collection** will take place in your timetabled lab sessions, and in independent study time shortly after those sessions.
2. **Analysis and discussion** should be done shortly after the lecture on the relevant topic.

The laboratories are aligned with much of the material which you will cover in lectures and seminars, so take the opportunities you have there to ask questions and check your understanding of the material.

Your Report Submission

You will submit a single report, as a single PDF file, covering all four laboratory exercises (three carried out in the light structures lab and one controlled remotely). Boxes like this one will indicate what you should add to that report and under what heading.

Aim for approximately six sides of A4 paper. This is not a limit, but a guide intented to help you avoid spending too much time on this exercise at the expense of other work on this course (which will prepare you for the exam) and work on other courses.

You may use pen, pencil and paper, or whatever software you prefer to carry out the calculations and draw the graphs required for this report. You should, however, show any calculation steps you have gone through for marking. One notable example is if you have used a standard tool in a piece of software to fit a line through some data, you should state how that line has been fitted. For example: “the line was fitted to minimise the sum of the square errors to the data, and forced to pass through (0,0)” or “this line was drawn by hand to pass through (0,0) and fitted by eye to the data”.

The report will be marked according to the university’s extended common marking scheme. Table 1.1 gives some extra guidance on what constitutes a “pass” (40% to 50%) and an “excellent” (above 70%) mark in this case.

Table 1.1: Specific guidance for marking scheme.

Criterion	Pass (40% to 50%)	Excellent (above 70%)
Accuracy of calculations (45% of total mark)	Calculations take the information provided and assess the parameters requested with few errors.	Calculations complete and accurate and show insight into structural mechanics that goes beyond simply applying the relevant equations.
Presentation of calculations and/or data (35% of total mark)	Calculations are clear and can be readily understood and followed, for example by a checking engineer.	The entire calculation set is clear and coherent, with diagrams, graphs and headings used precisely to present a calculation set which is easily understood. This is a near-professional standard.
Appreciation of experimental context (20% of overall mark)	Shows an appreciation that experiments are not perfect, and description of some of the effects of imperfections in the experiment on measurements.	Uses insight based on structural theory to critically appraise experimental methods and perhaps to suggest improvements.

2

Load and stress in a truss

This is a "remote laboratory". You are in control of the experiment, just as you would be if you were present in the laboratory, but you control it, and observe the outputs from the sensors, through a web browser.

In tutorial questions, we've asked you to take a truss with a load applied and calculate the forces, stresses and strains. This time, you can see the strains, and you need to calculate the force.

The truss is built from acrylic, with elastic modulus 2.5 GPa. The (nominal) width of the truss members is 25 mm, and their breadth is 10 mm. The geometry of the truss is shown in Figure 2.1.

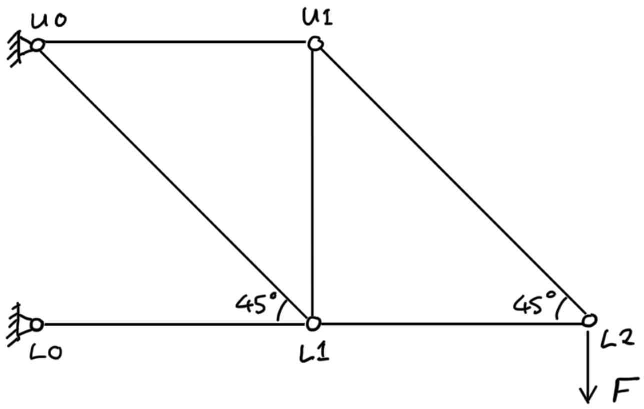


Figure 2.1: Truss geometry and loading

The overarching question is: what is the relationship between the force F on the truss and the slider value you enter to control the experiment?

2.1 Data collection

Tare the measurements so you have them all reading zero at the reference point when the slider is at zero. Record the strain measured at each guage as the slider is moved from zero to 20, in steps of two. Note that you don't have to do this by hand. You can use "Record Snapshot" to save the strain readings at that moment in time and then "Download Snapshots" to save them to your computer as a .csv (comma-separated values) file, which can be opened in Excel and other software.

Add to Section 1a of your report ($\approx$ half a page):

- A table of strain in each guage for each slider value from zero to 20. (5 marks for presentation)

2.2 Analysis

Plot all of these points on a graph of "slider value" against strain, one for each guage location. Fit six lines to these data points, one for each location. This can be done by hand or using software, but note that there is one point we know for sure for each line: the point (0,0) which you defined as the reference point at the start. The fitted lines should therefore all pass through this point. Find the slope of each line.

Use the truss analysis theory you have learned in lectures to write the relationship between an applied force F and the strain at each guage location. Use these relationships to write an expression for the slope of a graph of force F against strain for each guage. Compare these expressions with the measured slopes of the slider value vs strain graphs, and estimate the relationship between slider value and force.

Add to Section 1b of your report($\approx$ one page):

- A graph of “slider value” against strain, with an appropriate line fitted to the data for each strain guage. (5 marks for presentation)
- Your working to define a relationship between the unknown force F and the strain at each strain guage. (5 marks for accuracy)
- Your estimate of the relationship between slider value and force. (5 marks for accuracy)
- One sentence describing possible sources of error in this estimate. (5 marks for appreciation)

3

Composite action in a beam

3.1 Data collection

The apparatus used to investigate Euler's Beam Theory is shown in Figure 3.1. Weights are used to applied load to a beam, and the axial strain in the beam is measured using strain gauges. There are two beam sections to test:

- a "bonded" beam, made by bonding together aluminium and steel; and
- an "unbonded" beam, in which the aluminium and steel are not bonded together.

The beams are instrumented using the strain gauges numbered as shown in Figure 3.2. A strain data logger is used to measure the very small change in resistance of the strain gauge as they change length. The strain data logger gives readings in micro-strain (μ-strain, 10^{-6} strain).

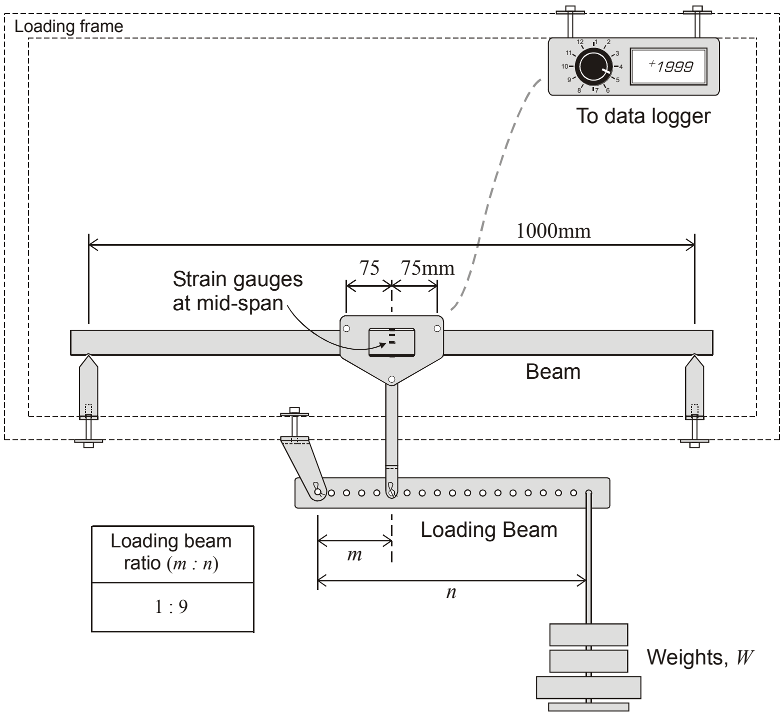


Figure 3.1: Composite beam test setup

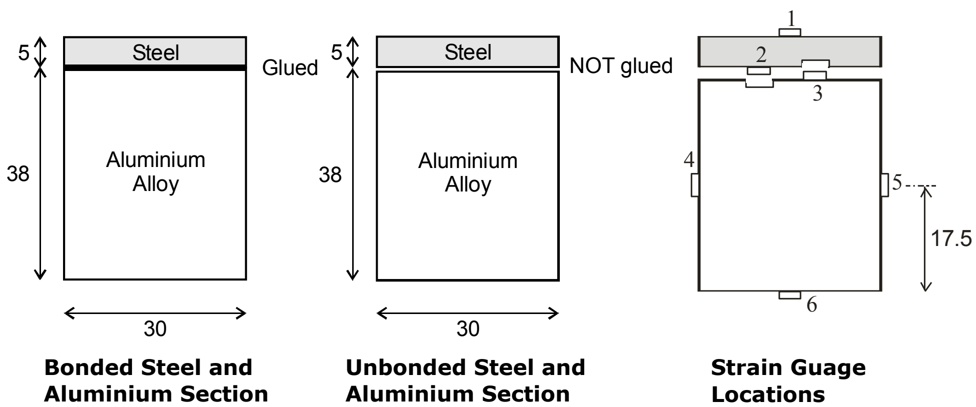


Figure 3.2: Bonded and unbonded composite beams (all dimensions in millimetres)

3.1.1 Carry out the experiment

1. "Zero" or "Tare" the strain measurements i.e., set to zero strain reading under zero load. Make sure only the empty hanger is suspended from the beam, click "Hardware" (in the menu bar), then click "Balance Gages".
2. Once you have done this, place weights on the hanger beneath the beam. First place 30 N, record the weight applied and the strain in each of the strain guages in a notebook.
3. Continue in 30 N intervals up to 150 N. At each point, record the weight applied and the strain in each of the strain guages in a notebook.
4. After you have collected strain data for each applied force, remove the weights.
5. Do the same for both the bonded and unbonded beams.

Add to Section 2a of your report (≈ half a page):

- Two tables, one for the bonded beam and one for the unbonded beam, with columns for the weight applied and the reading on each strain guage. (5 marks for presentation)

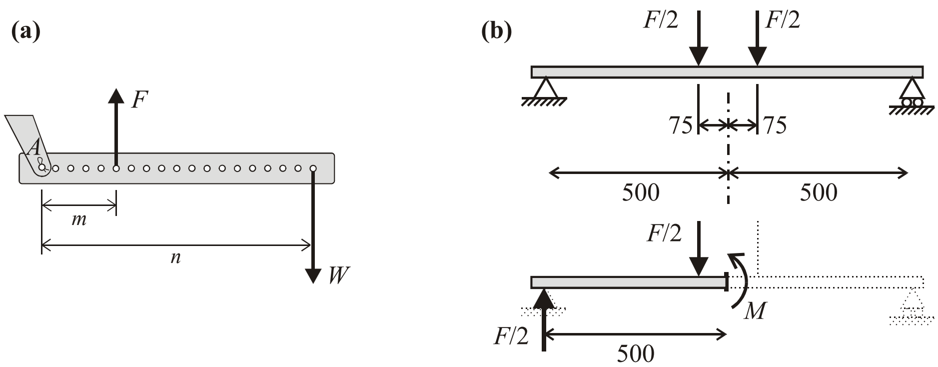


Figure 3.3: Diagrams showing **(a)** the loading lever system and **(b)** the structural diagram for the beam and a free body to find the moment at midspan

3.2 Analysis

Euler's Beam Theory is in terms of bending moment, so before starting the analysis, we need to determine how the bending moment, *M*, varies with the applied load, *W* from Figure 3.1.

Write an expression for the force *F* applied to the beam in terms of the weight *W*, and the dimensions *m* and *n*. To do this, you can take moments around the pivot point *A*, shown in Figure 3.3.

The load *F* is applied to the test beam as two point loads. Write an expression for the bending moment *M* at mid-span (where the strain guages are located) in terms of the force *F*, using the structural diagram and free body diagram shown in Figure 3.3.

You can now use the data you collected during the laboratory session to check the moment-strain relationship for the section. For the 150 N load on each beam, draw a graph of strain (*x*-axis) against vertical position (*y*-axis), using the dimensions in Figure 3.2. Draw these both on the same graph.

The geometry of the beams is shown in Figure 3.2, and the Young's moduli of the beam materials are given in Table 3.1. Using these, follow the process to calculate the second moment of area of an appropriate transformed section, and predict the strain distribution in the section.

Plot your prediction on the same two graphs as you plotted the strain distribution. Which of the experimental cross sections, bonded or unbonded, follows your predicted strain distribution most closely? Discuss why this is the case.

Table 3.1: Material properties

Material	Young's modulus
Steel	$E_s = 200\,\mathrm{kN/mm^2}$
Aluminium	$E_a = 70\,\mathrm{kN/mm^2}$

Add to Section 2b of your report ($\approx$ one page):

- Two tables, one for the bonded beam and one for the unbonded beam, with columns for the moment applied and the reading on each strain guage. (5 marks for accuracy)
- One graph, plotting strain against vertical position for the 150N weight for both beams on the same graph, and your theoretical prediction of strain against position. (5 marks for accuracy, 5 marks for presentation)
- A short explanation for the difference between the behaviour of each beam. (5 marks for appreciation)

4

Torsion of a shaft

4.1 Data collection

This piece of equipment (shown in Figure 4.1). Applies a torque to a shaft secured in two chucks. The loading rod is fixed to one of the chucks, and causes it to rotate. The masses can be placed on the loading rod to apply a known torque to the shaft.

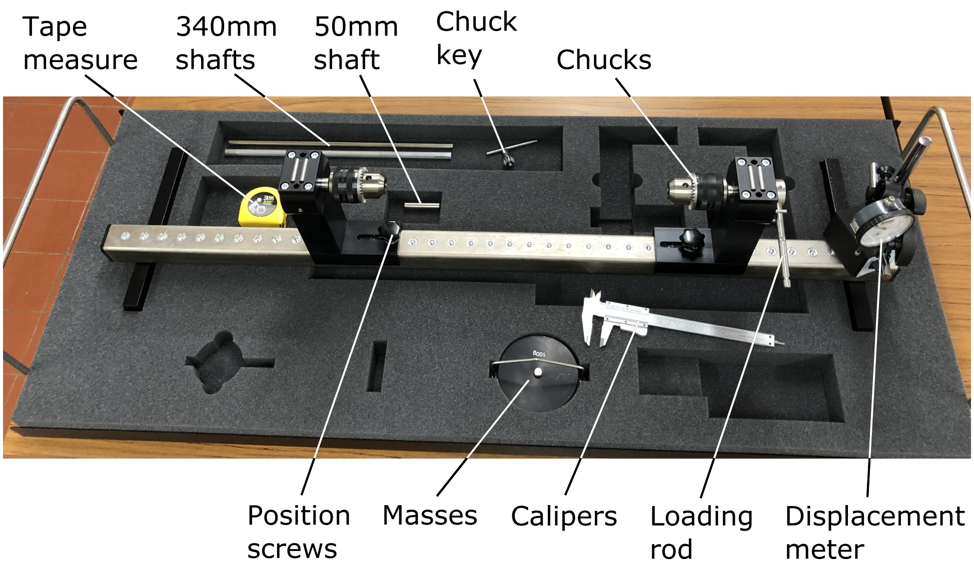


Figure 4.1: Torsion test equipment

The rotation of the shaft under torque is measured in this setup by measuring the vertical displacement of the rod which applies the torque. When a load is applied, however, there is some displacement (for example, due to bending of the bar) which is not due to torsion of the shaft. We'll call this the "equipment deformation". The first part of the experiment is to find out this deformation so that we can correct for it. To do this, we create an experiment where the torsion of the shaft is very close to zero.

4.1.1 Measure the equipment deformation

1. Take the 50 mm-long 12 mm-diameter steel bar.
2. Place it in the chucks and bring the chucks so that there is a very small ($\approx$ 1 mm) gap between them, tightening the chucks around the bar.
3. Bring the displacement guage into position and set to zero.
4. Apply a 0.9 kg weight to the rod, and note the displacement measurement.
5. Apply a 1.8 kg weight to the rod, and note the displacement measurement.

These displacements can be subtracted from all your other readings to leave only the component of displacement (and therefore rotation) due to the torsion of the bar.

4.1.2 Carry out the experiment

1. Measure and record the distance between the axis of rotation and the point at which the load hanger sits (the lever arm), and also the distance between the axis of rotation and the point where the displacement guage makes contact.
2. Take the 340 mm-long 8 mm-diameter steel bar.
3. Place it in the chucks and bring the chucks so that there is a 280 mm gap between them, tightening the chucks around the bar.
4. Bring the displacement guage into position and set to zero.
5. Apply a 0.9 kg weight to the rod, and note the displacement measurement.
6. Apply a 1.8 kg weight to the rod, and note the displacement measurement.
7. Repeat the process for the 12 mm diameter aluminium bar.

Add to Section 3a of your report (≈ half a page):

- A table showing the equipment deformation under 0.9 kg and 1.8 kg and the displacement reading from the guage for the 0.9 kg and 1.8 kg masses for each shaft. (2 marks for presentation)
- Notes on the geometry of the system: the length and diameter of the shafts; the lever arm for the applied mass and the offset of the displacement guage from the axis of rotation. (3 marks for presentation)

4.2 Analysis

You can now take the weight and displacement measurements you made and convert them into torque and rotation. Make a table showing:

- the weight applied;
- the displacement measured;
- the corrected displacement (after subtracting the equipment deformation);
- the torque applied (the weight multiplied by the lever arm); and
- the total rotation along the length of the shaft.

Plot rotation against torque for each shaft. Use the theory for torsion of a solid circular shaft to write an equation relating rotation and torque. Use your results to estimate the shear modulus for each material.

Add to Section 3b of your report (≈ one page):

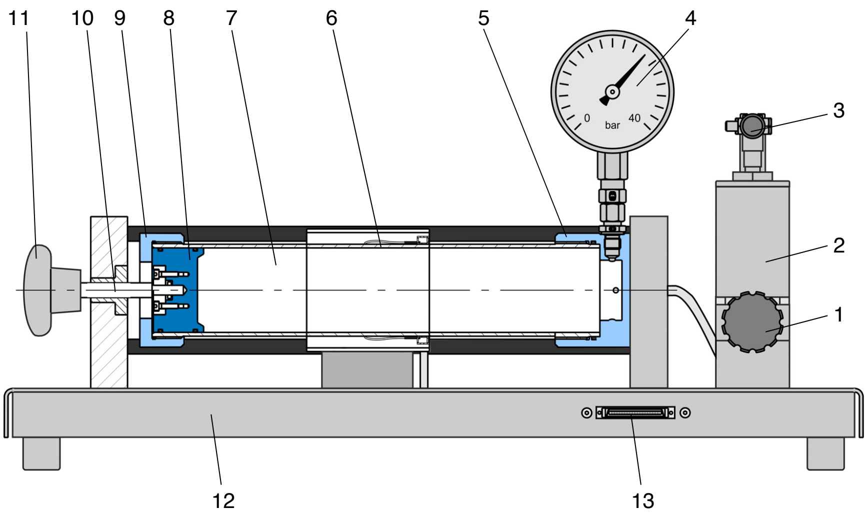
- A table showing weight, displacement, corrected displacement, torque and rotation. (5 marks for accuracy)
- A plot of rotation against torque for each shaft, on the same graph. (5 marks for presentation)
- An estimate, showing your working, of the shear modulus for each material. (5 marks for accuracy)
- A short discussion of possible sources of error in your estimate. (5 marks for appreciation)

5 Membrane stresses in a pressure vessel

5.1 Data collection

The pressure vessel experiment (Figure 5.1) is used to demonstrate the plane stress state in a thin-walled cylinder subject to internal pressure. The strain state in the walls of the cylinder is measured using a series of strain guages. The pressure is generated by a hydraulic pump and displayed on a manometer.

Figure 5.1: Pressure vessel equipment



Item	Name	Item	Name
1	Relieve knob	8	Closure piston
2	Hydraulic cylinder	9	Supporting collar
3	Pump lever	10	Threaded spindle
4	Manometer	11	Handwheel for piston adjustment
5	Fixed lid	12	Base plate
6	Strain gauge application	13	Connecting socket
7	Cylinder		

Figure 5.2: Pressure vessel test setup

The details of the equipment are shown in Figure 5.2. A thin-walled cylinder (7) made of aluminium is the core of the device. On one side, the cylinder is closed by a bolted-on lid (5). On the other side, the cylinder is closed by a closure piston (8). The closure piston is operated by a handwheel (11) and a threaded spindle (10).

The cylinder is filled with hydraulic oil. The desired internal pressure is generated by a hand-operated hydraulic pump and displayed on a manometer (4).

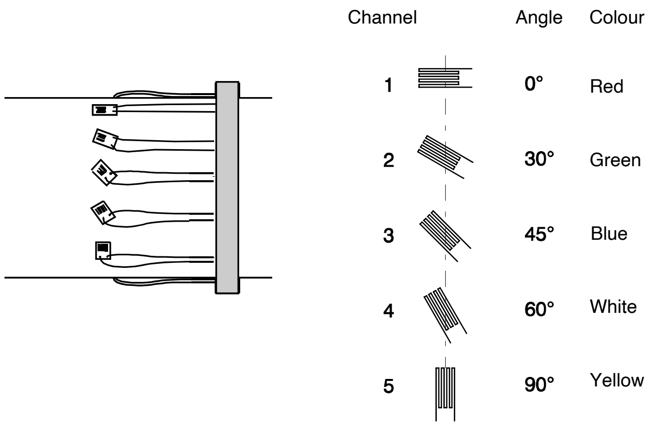
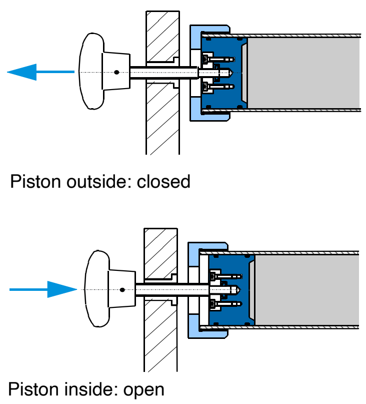


Figure 5.3: Arrangement of strain gauges on the cylinder wall



With the piston (8) in the outer position, the pressure on the front face is supported by the piston and a collar (9) bolted onto the cylinder. The biaxial stress state of a closed vessel applies.
With the piston (8) in the outer position, the pressure on the front face is supported through the base frame. No load is placed on the cylinder in longitudinal direction. The uniaxial stress state of an open pipe applies.

Strain gauges (7) are arranged around the circumference of the cylinder to measure the strain in the aluminium, which you will use in your analysis later. A total of five points on the cylinder are measured, at varying orientations of 0°, 30°, 45°, 60° and 90° relative to the cylinder axis. The angle 0° therefore corresponds to the axial direction, and the angle 90° to the tangential direction. The measurement channels are assigned to the strain gauges as shown in Figure 5.3.

5.1.1 Carry out the experiment

NOTICE

Monitor the pressure on the manometer, and do not exceed 30 bar. This could cause the membrane to yield, or the hydraulic system to leak. The safety valve is actuated at approximately 35 bar.

1. Ensure that the data logger screen shows strain readings for guages 1 to 5.
2. Screw out the relieve knob ((1) in Figure 5.2) to depressurise the device.
3. Since the pressure is now zero, touch the “T” button on the touchscreen to set the strains to zero.
4. Unscrew the piston all the way out using the handwheel (11).
5. Screw in the relieve knob (1).
6. Use the hand lever (3) at the hydraulic pump to build up to a pressure of 20 MPa.
7. If the pressure drops slightly at first, readjust with the hydraulic pump.
8. Check whether the piston is in contact with the collar of the cylinder by turning the handwheel (11) slightly. It should move freely.
9. Read off and note down the strain from channels 1 to 5 in a table, noting the guage orientation for each channel. Label this as the “closed” condition.
10. Screw out the relieve knob (1) to depressurise the device.

You can now carry out the same process for the “open” condition of the cylinder.

1. Screw out the relieve knob (1) to depressurise the device.
2. Check that the channel readings at a pressure of 0 bar are very close to zero.
3. With the relieve knob (1) still unscrewed, screw in the piston using the handwheel (11).
4. Screw in the relieve knob (1).
5. Use the hand lever (3) at the hydraulic pump to build up to a pressure of 20 MPa.

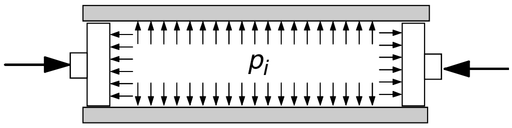
6. If the pressure drops slightly at first, readjust with the hydraulic pump.
7. Read off and note down the strain from channels 1 to 5 in a table, noting the guage orientation for each channel. Label this as the “open” condition.
8. Screw out the relieve knob (1) to depressurise the device.
9. Check that the channel readings at a pressure of 0 bar are very close to zero.

Add to Section 4a of your report (≈ half a page):

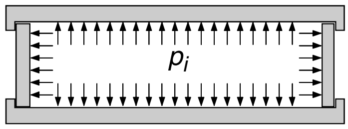
- A table showing the strain at each guage in the open and closed condition at a pressure of 20 MPa. (5 marks for presentation)

Table 5.1: Properties of aluminium pressure vessel

Length	400 mm
Outer diameter:	75 mm
Wall thickness:	2.5 mm
Elastic modulus	70 kN/mm^2
Poisson's ratio	0.33
Yield strength	270 MPa



Open cylinder



Closed cylinder

Figure 5.4: Pressures and forces on the cylinder

5.2 Analysis

Predict the longitudinal and hoop stress in the wall of the pressure vessel using theory for membrane stresses in pressure vessels and the geometry and material properties given in Table 5.1 and the pressure of 20 MPa you applied during the experiment. Do this for both the “open cylinder” and “closed cylinder” conditions, as shown in Figure 5.4.

Draw Mohr's circle for stress for these two cases on the same graph, using your predicted stresses, and based on the principal stresses, use an appropriate method to calculate the pressure you would expect to cause yield in the aluminium.

Remember, in the experiment you measured strain, not stress (stress is very difficult to measure directly). Using the material properties from Table 5.1, calculate the hoop strain you would expect due to your predicted hoop stress.

In the closed cylinder, the longitudinal stress will also cause a strain in the hoop direction. Calculate the longitudinal strain due to hoop stress and superimpose the two to estimate the total longitudinal strain due to the

20 MPa pressure.

Go through the equivalent process to estimate the hoop strain.

Compare your predictions and the measured strains in the 0° and 90° directions. How closely do they match? Discuss any possible sources of error in either value.

Add to Section 4b of your report (≈ one page):

- Your theoretical predictions of stress in the two conditions, and Mohr's circle for each drawn on the same graph. (5 marks for accuracy)
- Your calculation for the pressure which would cause yield in the aluminium. (5 marks for accuracy)
- Your theoretical predictions of hoop and longitudinal strain in each condition, showing all your working. (5 marks for accuracy)
- A comparison between your predictions and the measured strains in the 0° and 90° directions, and discussion of any possible sources of error. (5 marks for appreciation)