# STR15
# Plastic Bending of Beams: Lecturer Guide



All due care has been taken to ensure that the contents of this manual are accurate and up to date. However, if any errors are discovered please inform TQ so the problem may be rectified.

A Packing Contents List is supplied with the equipment. Carefully check the contents of the package(s) against the list. If any items are missing or damaged, contact your local TQ agent or TQ immediately.

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**TQ Education and Training Ltd**
**Products Division**

# Contents

# SECTION 1 INTRODUCTION

The Plastic Bending of Beams experiment gives students a visualisation and proof of basic concepts such as the form factor, plastic hinges and plastic collapse. This provides a sound foundation for further work. The experiments are quick, clear and accurate, and ideal for students working on their own or in groups.

The Plastic Bending of Beams experiment is part of a modular range of equipment that teaches the fundamentals of structures. This range is a modern, productive, time-efficient and cost-effective way your students can learn about structures. You will find it invaluable for teaching structural principles in many branches of mechanical, aeronautical and civil engineering.

This Lecturer Guide gives details about the equipment and describes how to set it up and use it. It also gives advice on care and maintenance and includes typical results for the experiments described in the Student Guide.

For convenience, you may copy the experiment procedures in the accompanying Student Guide and give to students as a laboratory worksheet. For detailed theory of plastic collapse and form factor students should refer to the textbook supplied with the Structures Test Frame (STR1).

# SECTION 2 DESCRIPTION

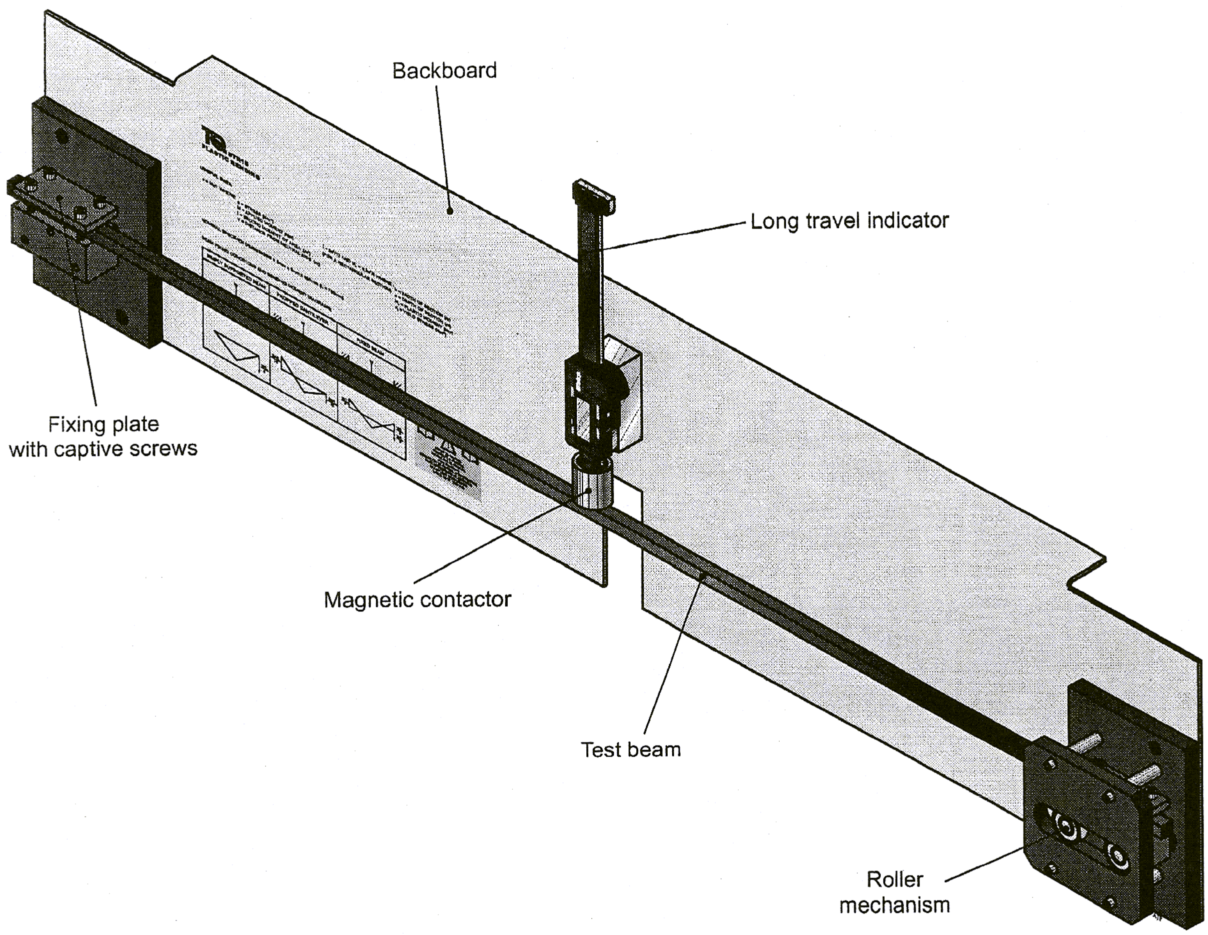



*Figure 1 Plastic Bending of Beams Experiment*

Like other experiments in the TQ Structures Range, the Plastic bending of beams experiment fits into the Structures Test Frame (STR1). The Structures Test Frame is a sturdy aluminium frame which stands on a workbench.

Loads are applied to the experiment using an electronic load cell. The Digital Force Display (STR1a) electronically measures and displays the force during experiments. It conveniently fixes to the Test Frame. All the equipment can be connected to a computer by means of an Automatic Data Acquisition Unit and software (STR2000).

Figure 1 shows the Plastic Bending of Beams experiment. It consists of a backboard on which a fixed and rolling chuck is attached, these chucks hold the specimen beams in various configurations during the tests. The rolling chuck is designed to restrain the bending moment exerted by a fixed beam whilst moving inward as the effective distance between the supports reduces as large deformations occur. Also attached to the backboard is a long travel digital indicator which is used for accurately measuring the deflection of the specimen beams. The indicator has a resolution of 0.01 mm and a travel of around 100 mm The contactor has a magnet built in to ensure contact between the indicator and the loading pin of the load cell.

There are diagrams and reference information printed on the equipment for student use.

A simple plastic vernier is supplied for students to measure the dimensions of the section, if better accuracy is required then a micrometer can be used for this purpose (not supplied).

Black hot rolled material would be the norm for structural steel work due to its ability to undergo large plastic deformations at constant stress. This is fundamental to plastic theory. The disadvantage to using this material in the laboratory is that the black hot rolled steel generally has very rounded corners making the accurate calculation of the second moment of area difficult. Also there is often a thick hard crust which distorts results when testing at this scale.

The specimens provided are fully annealed from cold rolled mild steel. The cold rolled and annealed specimen has the same strain properties of the hot rolled steel, but has much sharper corners and a thinner oxide crust. The specimens are 8 mm square and 860 mm long.

Specimens can be reused after a series of tests by annealing in an oven at 800 – 900$^{O}$C for at least 1 hour and left to cool slowly in the oven. However additional specimens are available from TQ Education and Training Limited or the importer.

## Operating Conditions

| | |
|---|---|
| **Storage temperature range** | –25°C - +55°C (when packaged for transport) |
| **Operating temperature range** | +5°C - +40°C |
| **Operating relative humidity range** | 80% at temperatures ≤ 31°C decreasing linearly to 50% at 40°C |
| **Operating environment** | Laboratory environment |

## How to Set Up the Equipment

The 'Packing Contents List' supplied is a list of items provided with the apparatus to enable normal use of it during the warranty period. If any item is missing or damaged, contact TQ or the importer.

A protective coating may have been applied to parts of this apparatus to prevent corrosion during transport. Remove the coating with paraffin or white spirit, and a cloth or brush.

***The maximum force exerted by the load cell should be 600N. Loads in excess of this will permanently elongate the load ring severely impairing its function and accuracy.***

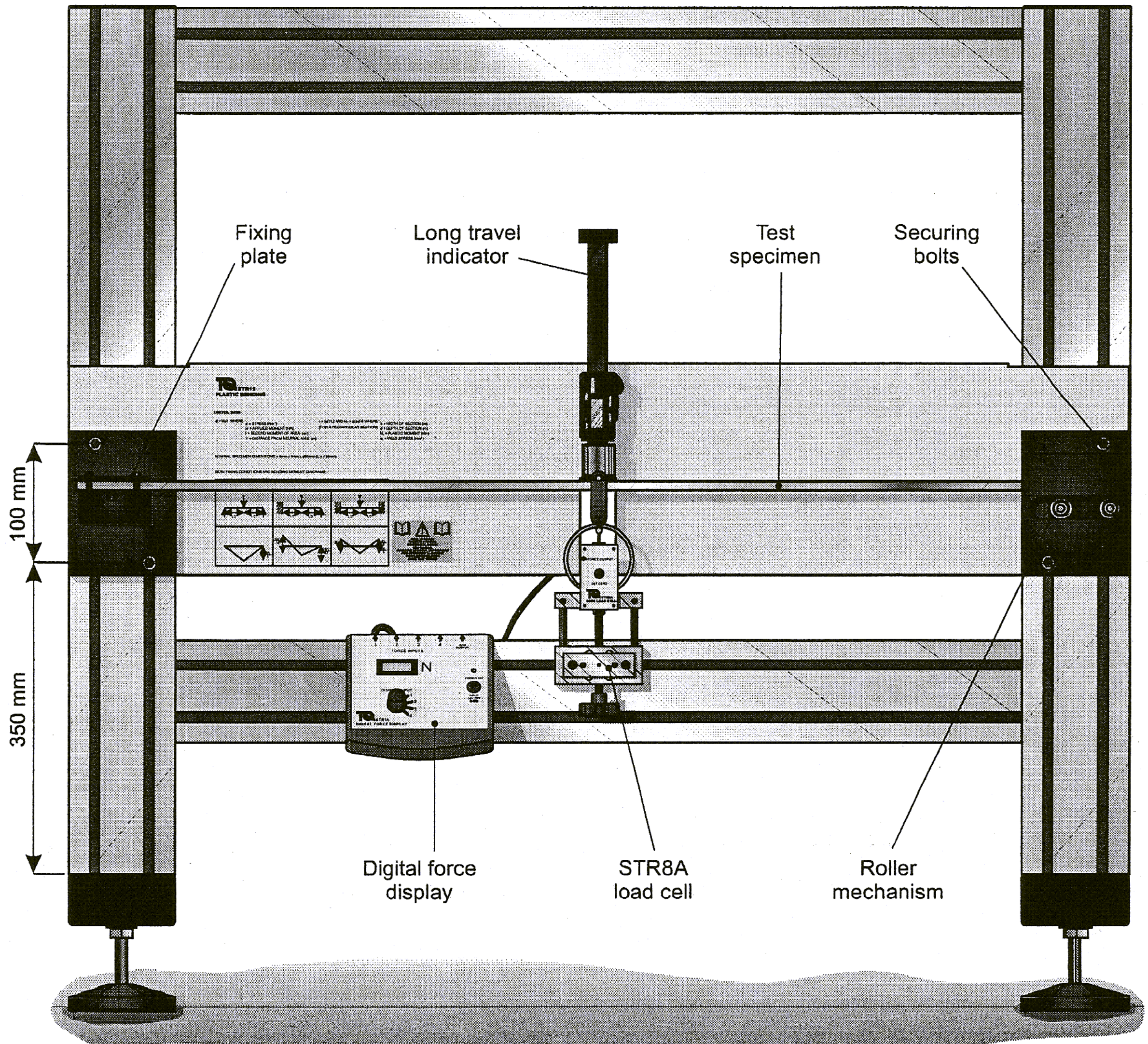



*Figure 2 Plastic Bending of Beams Experiment in the Structures Frame*

Figure 2 shows the Plastic Bending of Beams experiment assembled in the Structures Test Frame. Before setting up and using the equipment, **always:**

- Visually inspect all parts (including electrical leads) for damage or wear. Replace as necessary.
- Check electrical connections are correct and secure. Electrical maintenance must only be carried out by a competent person.
- Check all components are secured correctly and fastenings are sufficiently tight.
- Position the Test Frame safely. Make sure it is on a solid, level surface, is steady, and easily accessible.

When the equipment is in use, **always:**

- Make sure students are adequately supervised.
- Comply with any statutory requirements that are in force about the installation, operation and maintenance of this apparatus in the country where it is to be used.
- Ensure excessive loads are **never** applied to any part of the equipment.

The equipment is easy to set up and for convenience or additional educational value you may wish your students to assemble it. Therefore the Student Guide also contains the following instructions. However, it will save student time if yourself or a technician completes the following instructions.

1. Place an assembled Test Frame (refer to the separate instructions supplied with the Test Frame if necessary) on a workbench. Make sure the 'window' of the Test Frame is easily accessible.

2. There are two securing nuts in each of the side members of the frame (on the inner track). Move one from each side to the outer track (see STR1 instruction sheet) then slide all four nuts to approximately the positions shown in Figure 2.

3. Slide two nuts into position for the load cell and fix the load cell leaving the screws slightly loose at this point.

4. Temporarily remove the long travel indicator from the unit and lift the unit into position, secure with the screws provided, level the ends of the unit with the frame.

5. Temporarily remove the fixing plates from the unit and rest a straight specimen across the chucks.

6. Adjust the position of the load cell until it is in the vertical position. Lock the load cell in the vertical position using the locking pin provided into one of the securing screw holes. Tighten the load cell using the 6 mm A/F Allen key.

7. Adjust the height of the load cell using the mechanism until the loading pin can pass through the holes in the load cell fork above the specimen. Adjust the height of the load cell until the pin is just about to touch the specimen ***do not apply a load to the specimen at this point***.

8. Remove the specimen beam and replace the indicator on the backboard. Check that there is at least 40 mm of downward travel available on the load cell before it hits the bottom stops; if there is not then move the back board up in the frame by the required amount.

9. Make sure the Digital Force Display is 'on'. Connect the mini DIN lead from 'Force Input 1' on the Digital Force Display to the socket marked 'Force Output' on the left-hand side of the load cell.

10. With no load on the load cell zero the reading using the knob on the front of the load cell.

## Care and Maintenance

If the unit needs cleaning, use a dry, lint free cloth. Do not allow water or other liquid to come into contact with either the bearings, electronic circuitry, the Load Cell or Digital indicator.

The load cell is factory calibrated and should not need recalibrating during the life of the unit. Do not expose the unit to shock forces (for example by dropping the unit). This may damage the potentiometer element in the load cell and impair its accuracy.

The best place to store the experiment is in position on a test Frame with no load on the load cell. Other than this remove the digital indicator, load cell and backboard and store it in a dry dust free environment.

## Spare Parts

Refer to the 'Packing Contents List' for any spare parts supplied with the apparatus. Contact TQ or the importer if you need any other spare parts.

# SECTION 3 EXPERIMENTS AND SAMPLE RESULTS

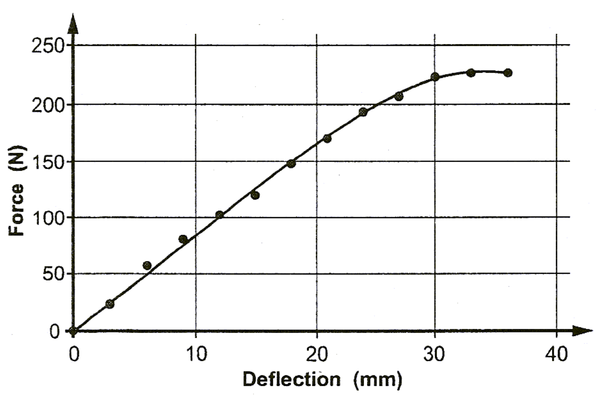
This section gives typical results for the sample experiments described in the Student Guide (the Student Guide details the methods). Please note that actual results may vary slightly from the numbers given, so **interpret these results as a general guide only.**

## Experiment 1: Plastic Bending of a Simply Supported Beam

In the following experiment students test a simply supported beam to find the form factor and examine the load deflection relationship for a beam which is taken to the point of plastic collapse.

| Deflection (mm) | Force (N) |
|---|---|
| 0 | 0 |
| 3 | 23 |
| 6 | 57 |
| 9 | 80 |
| 12 | 103 |
| 15 | 120 |
| 18 | 148 |
| 21 | 171 |
| 24 | 194 |
| 27 | 207 |
| 30 | 223 |
| 33 | 227 |
| 36 | 227 |

*Table 1 Results for Experiment 1*




*Graph 1 Force versus Deflection for a Simply Supported Beam*

Students should comment that the beam bends elastically and then at yield then there is an increasing rate of deformation with load. They should also sketch the collapsed beam with a single plastic hinge.

From measurement specimen beam = 7.90 mm square therefore $I = 3.25 \times 10^{-10} m^4$

At this point students will require a yield stress for the specimen material. Nominally, this is 325MPa for the steel used.

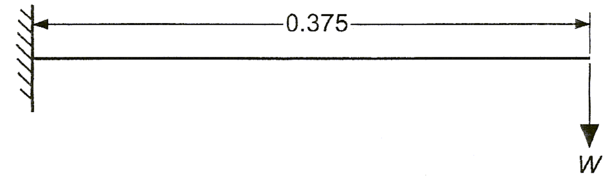



*Figure 3 A Cantilever Test to Establish Beam Material Yield Stress*

An accurate value can be obtained by testing a specimen as a cantilever as shown in figure 3 (a used simply supported specimen is suitable, be careful to ensure that the plastic hinge is not at the root of the cantilever)

Bend the specimen and obtain the collapse load

The following equation can be used to obtain the value of yield stress:

$\sigma_y = 4WL/bd^2$

Where:

$\sigma_y$ = Yield Stress (Pa)
W = The collapse load of the beam (N)
L = length of cantilever (m) = 0.375m
b = Width of beam (m)
d = depth of beam (m)

This test can form part of the laboratory session but has been left out of the student guide as it may confuse students.

For the simply supported beam:

Experimental collapse load = 227N

Therefore the maximum bending moment ($M_p$) = $WL/4 = (227 \times 0.75)/4 = 42.5$ Nm

From a yield stress of 325MPa the bending moment at yield of the extreme fibre ($M_y$) = $\sigma_y I/y$ = 30Nm

Where:

$\sigma_y$ = Yield Stress (Pa)

I = Second moment of area of specimen ($m^4$) = $3.25 \times 10^{-10} m^4$

y = Distance from extreme fibre to neutral axis (m) = $3.95 \times 10^{-3}$m

Therefore the experimental form factor = $M_p/M_y$ = 42.5/30 = 1.42

Text book value = 1.5

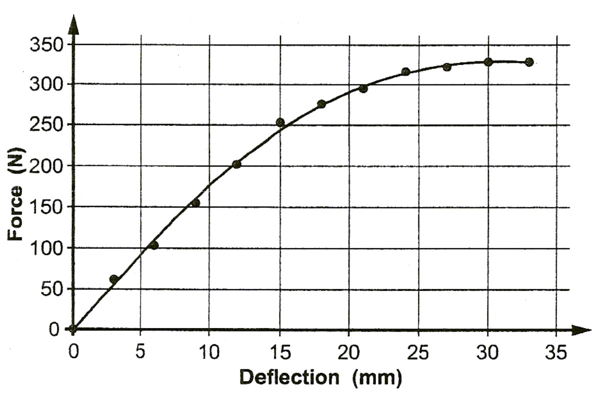
Students should discuss the advantages of using plastic beam theory when designing structures in terms of additional factors of safety and economy.

## Experiment 2: Comparison of Collapse Loads for Various Beam Fixing Conditions

In this experiment students compare the collapse modes of a simply supported beam, a propped cantilever and a fixed beam.

| Deflection ( mm) | Force (N) |
|---|---|
| 0 | 0 |
| 3 | 62 |
| 6 | 104 |
| 9 | 155 |
| 12 | 203 |
| 15 | 254 |
| 18 | 276 |
| 21 | 296 |
| 24 | 317 |
| 27 | 323 |
| 30 | 329 |
| 33 | 329 |

*Table 2 Results for Experiment 2 (propped cantilever)*



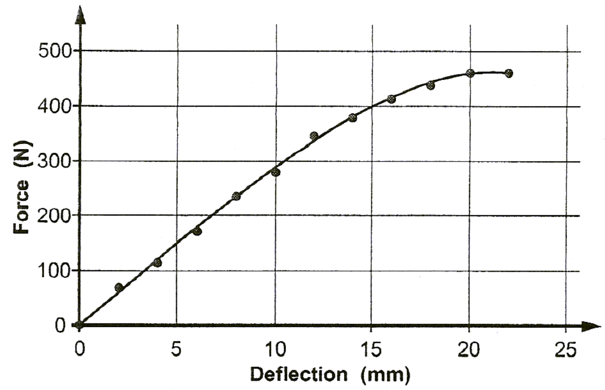

*Graph 2 Force vs Deflection: Propped Cantilever*

Students should sketch the collapsed propped cantilever with a plastic hinge at the root and a plastic hinge at the centre point.

| Deflection (mm) | Force (N) |
|---|---|
| 0 | 0 |
| 2 | 69 |
| 4 | 113 |
| 6 | 171 |
| 8 | 236 |
| 10 | 280 |
| 12 | 347 |
| 14 | 380 |
| 16 | 414 |
| 18 | 438 |
| 20 | 460 |
| 22 | 460 |

*Table 3 Results for Experiment 2 (fixed beam)*

Students should sketch the collapsed fixed beam with three plastic hinges: one at each root and one at the centre line.




*Graph 3 Force v Deflection: Fixed Beam*

Theoretical ratio of collapse loads:

Simply supported beam: propped cantilever: fixed beam = 1:1.5:2

Experimental ratio from above results = 1:1.46:2.03

Students should note that the ratio of collapse load is proportional to the maximum bending moment of each of the beams. The propped cantilever however is more difficult to predict by inspection since the two hinges form at positions where the bending moments are slightly different (3WL/16 and 5WL/32). A co mmon approach is to use external and internal work

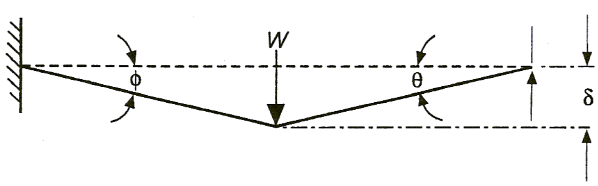



*Figure 4 External work and internal work in a propped load*

$$\text{External Work} = W\delta$$

$$\text{Internal Work} = M_p\phi + M_p(\phi + \theta)$$

$$\phi = \frac{\delta}{0.5L} \qquad \theta = \frac{\delta}{0.5L}$$

$$\therefore M_p\left(\frac{2\times 2\delta}{L} + \frac{2\delta}{L}\right) = W\delta$$

$$M_p\left(\frac{6\delta}{L}\right) = W\delta$$

$$M_p\left(\frac{W\delta}{6\delta/L}\right) \qquad \therefore M_p = \frac{WL}{6}$$

Ratio to simply supported beam

$$= \frac{\text{WL}}{4} \div \frac{\text{WL}}{6} = 1.5$$

## Description

The Structures Load Cell (STR8a) applies controlled loads to a variety of TQ Structures Range experiments. Figure A1 shows the Structures Load Cell.

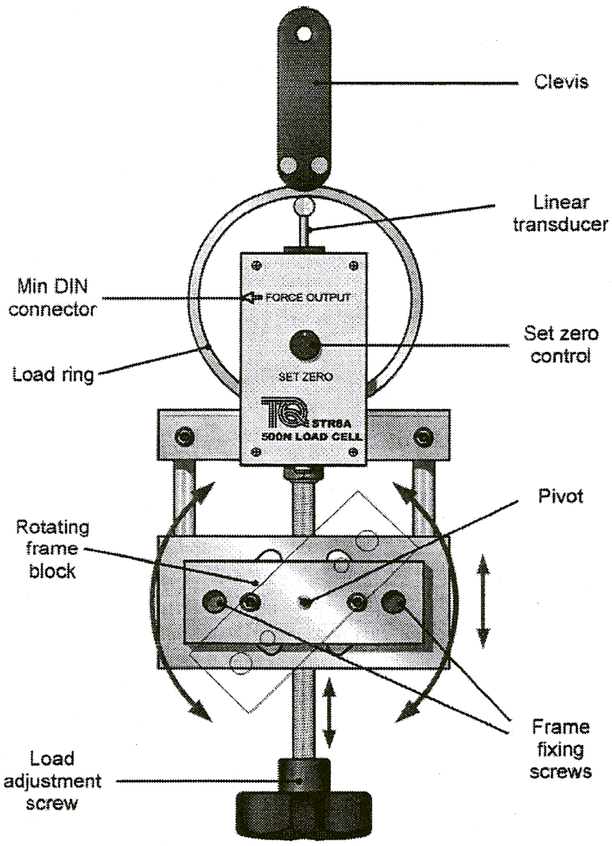



*Figure A1 Structures load cell*

The Load Cell applies loads in the range of 0 - 500 N. The force exerted is controlled using the load adjustment screw. The securing block for fixing the Load Cell to the test frame pivots, and this allows angled loads to be applied. A mini DIN output allows connection to a Digital Force Display (STR1A) which shows the actual loads.

## Operating Conditions

Table A1 shows the working limits of the Load Cell. Do not exceed any of these limits.

| | |
|---|---|
| **Storage temperature range:** | –25°C - +55°C (when packaged for transport) |
| **Operating temperature range:** | +5°C - +40°C |
| **Operating relative humidity range:** | 80 % at temperatures ≤ 31°C decreasing linearly to 50 % at 40°C |
| **Operating environment:** | Laboratory environment |

*Table A1 Operating Limits*

Before setting up and using the equipment, **always:**

- Visually inspect all parts (including electrical leads) for damage or wear. Replace as necessary.
- Check electrical connections are correct and secure. Electrical maintenance must only be carried out by a competent person.
- Check all components are secured correctly and fastenings are sufficiently tight.
- Position the Test Frame safely. Make sure it is mounted on a solid, level surface, is steady, and easily accessible.

When the equipment is in use, **always:**

- Make sure students are adequately supervised.
- Comply with any statutory requirements that are in force about the installation, operation and maintenance of this apparatus in the country where it is to be used.

## Setting up the Equipment

The 'Packing Contents List' supplied is a list of items provided with the apparatus to enable normal use of it during the warranty period. If any item is missing or damaged, contact TQ or the importer.

A protective coating may have been applied to parts of this apparatus to prevent corrosion during transport. If so, remove the coating with paraffin or white spirit, and a cloth or brush.

## How to fit the Load Cell

Figure A2 and Figure A3 show the load cell mountings. One end fits to the Test frame by means of two 6 mm A/F Allen screws. The other end fits onto a suitable mounting by means of a connecting pin.

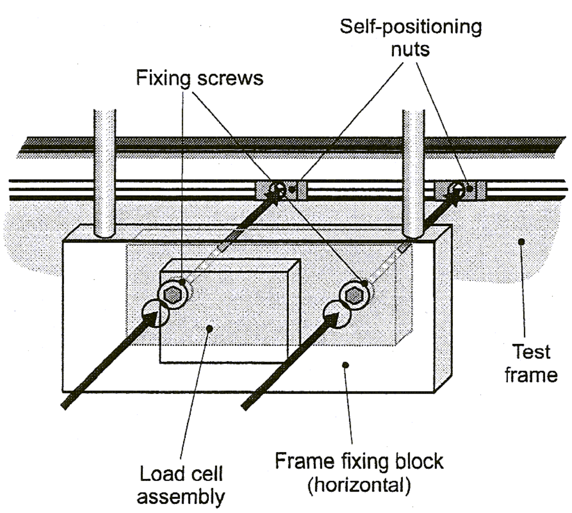



*Figure A2 Fixing the load cell to the test frame*

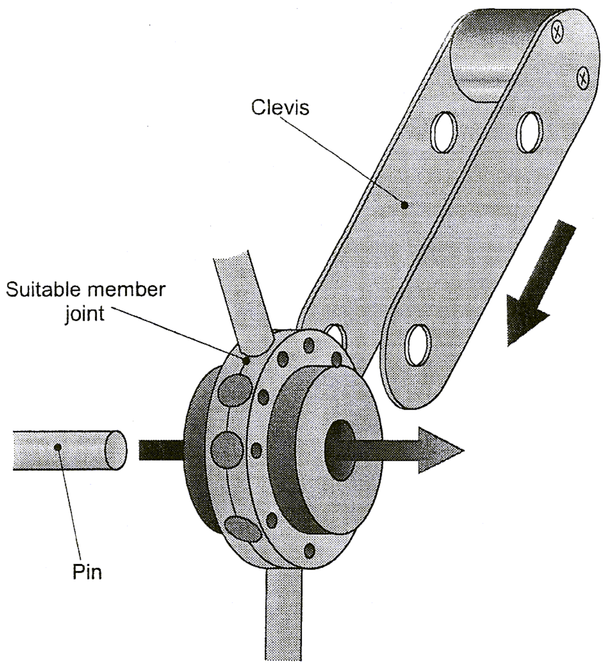



*Figure A3 Typical fitting of the clevis to an experiment*

To fit the Load Cell:

1. Ensure that the frame mounting block is horizontal, to allow access to the fixing screws, locate the screws into the self positioning nuts (Figure A2).
2. Leaving the screw loose for fine adjustment later, fix the load cell into position as required.
3. Position the clevis as desired and then connect using a pin (Figure A3).

## *Connecting the Digital Force Display (STR1A)*

The Load Cell is connected to the Digital Force Display to gain a reading of force.

The display connects to the load cell using the lead with a four-way mini DIN plug at each end. Connect one end of the lead to any of the four sockets marked "Force Input" on the Digital Force Display and connect the other end of the lead to the socket on the load cell marked "Force Output".

## *Care and Maintenance*

If the Load Cell needs cleaning, use a dry, lint free cloth. Do not allow water or other liquid to come into contact with either the bearings or electronic circuitry of the load cell.

Do not use the load cell to apply loads greater than 500 N. Loads more than this may permanently deform the load ring, impairing the function and accuracy of the load cell.

The load cell is factory calibrated and should not need recalibrating during the life of the unit. Do not expose the force sensor to shock forces (for example by dropping the unit). This may damage the potentiometer element in the load cell and impair its accuracy.