HIGHER
ENGINEERING
SCIENCE

Material Engineering

Name ______________________________

Class ______________________________

Teacher ____________________________

Ellon Academy
Technical Faculty

Learning Intentions

- I will learn about the properties of materials and how they are applied in the real world.
- I will learn about stress and strain, and Young's Modulus
- I will learn how to draw a stress/strain graph
- I will learn about factor of safety and why it is important in structural engineering

Success Criteria

I can develop structural solutions to solve complex problems by:

- Identifying key aspects of the problem
- Applying knowledge and understanding of structures, materials and/or mechanisms
- Carrying out calculations to assist the selection of materials or component sizes

To access video clips that will help on this course go to **www.youtube.com/MacBeathsTech**

What is a Material Engineer?

Materials Engineers carry out research into the behaviour of materials under different conditions. Materials engineers are responsible for the research, specification, design and development of materials to advance technologies of many kinds. Their expertise lies in understanding the properties and behaviours of different substances, from raw materials to finished products

Working in a diverse range of industries, materials engineers combine or modify materials in different ways to improve the performance, durability and cost-effectiveness of processes and products

They can work with existing materials like carbon fibres, metals, plastics and ceramics, to newer ones like graphene and phosphorene.

In the context of this course we will focus on the structural Engineering aspects that can exist within this career path.

Properties Of Materials

It is not only the shape of a structure that will influence its overall performance that you have learned about in the previous topic, but the material that each member in the structure is made from. If any one member was to fail within the structure itself, it would create a domino effect on the other members and ultimately the structure would collapse.
In order to select a material for a particular purpose the structural engineer must consider a range of materials, all with different properties. The engineer will then choose the material that is best suited to the job in hand.

The most common properties to be considered include:

1. STRENGTH – the ability of a material to resist force. All materials have some degree of strength – the greater the force the material can resist, the stronger the material. Some materials can be strong in tension but weak in compression, for example mild steel. The converse can also be true, as is the case with concrete, which is strong in compression but weak in tension. Hence, the reason that concrete is often reinforced with mild steel.

2. ELASTICITY – the ability of a material to return to its original shape or length once an applied load or force has been removed. A material such as rubber is described as elastic because it can be stretched but when it is released it will return to its original condition.

3. PLASTICITY – the ability of a material to change its shape or length under a load and stay deformed even when the load is removed.

4. DUCTILITY – the ability of a material to be stretched without fracturing and be formed into shapes such as very thin sheets or very thin wire. Copper, for example, is very ductile and behaves in a plastic manner when stretched.

5. BRITTLENESS – the property of being easily cracked, snapped or broken. It is the opposite of ductility and therefore the material has little plasticity and will fail under loading without stretching or changing shape. Cast iron and glass are obvious examples of materials that are brittle.

6. MALLEABILITY – the ability of a material to be shaped, worked or formed without fracturing. It is closely related to the property of plasticity.

7. TOUGHNESS – the ability to absorb a sudden sharp load without causing permanent deformation or failure. Tough materials require high elasticity.

8. HARDNESS – the ability to resist erosion or surface wear. Hard materials are used in situations where two surfaces are moving across or over each other.

Materials Testing

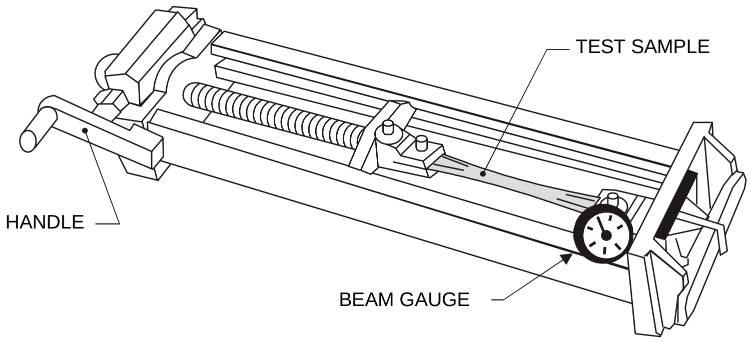
In order to discover the various properties of a material we must carry out material tests. There are many different types of tests available but the most common is the tensile test. As the name suggests the material is subjected to a tensile force or in other words, the material is stretched or pulled apart.

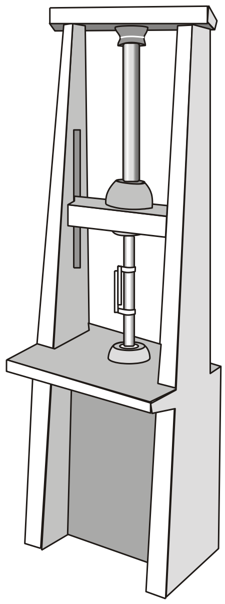
Results from tensile tests allow us to determine the following properties:

1. The elasticity of a material
2. The plasticity or ductility of the material
3. The ultimate tensile strength of the material.

Tensile Testing

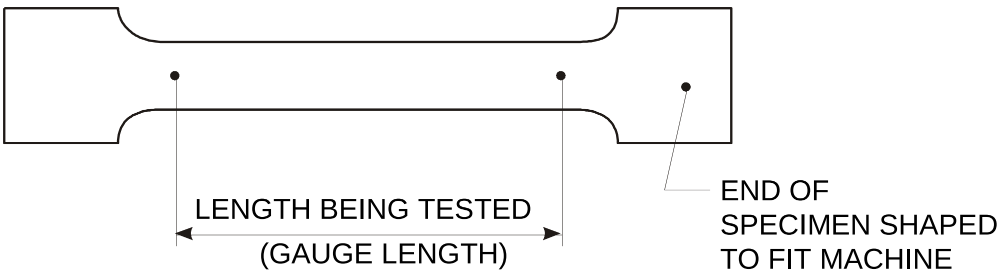
A tensometer or tensile testing machine is designed to apply a controlled tensile force to a sample of the material.





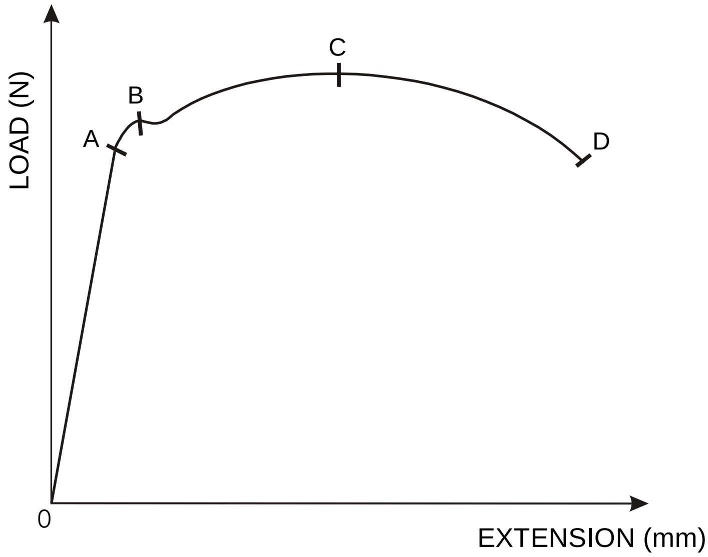
More complex machines can even plot a graph of how the material behaves during the test.

In order for tests to be carried out on a consistent basis, the shape of the specimen to be tested must conform to British Standards. The test sample is prepared to have a thin central section of uniform cross-section. A typical test specimen is shown below.



The principle of tensile testing is very simple. As the force is applied to the specimen, the material begins to stretch or extend. The tensometer applies the force at a constant rate and readings of force and extension are noted until the specimen finally breaks. These readings can be plotted on a graph to show the overall performance of the material.

The results of a typical tensile test for a sample of mild steel are shown.



The shape of the graph is very important and helps us predict how the material will behave or react under different loading conditions.

Between points O and 'A' the material behaves elastically and this part of the graph is known as the **elastic region**. This means that the material stretches under the load but will return to its original length when the load is removed. In fact, the force and extension produced are proportional and this part of the graph will be a straight line. This relationship is known as Hooke's Law and is very important to structural engineers.

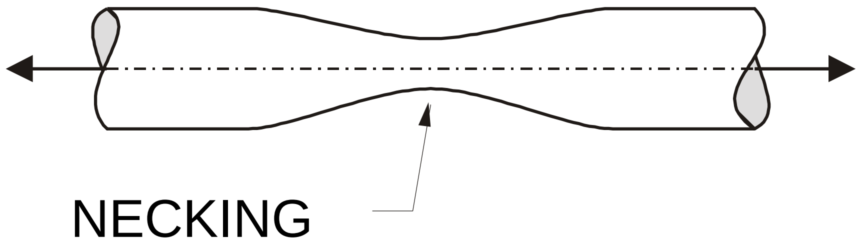
Point 'A' is called the **Limit of Elasticity** and any loading beyond this point results in plastic deformation of the sample.

Point 'B' is called the **yield point** and a permanent change in length results even when the load is removed. Loading beyond this point results in rapidly increasing extension.

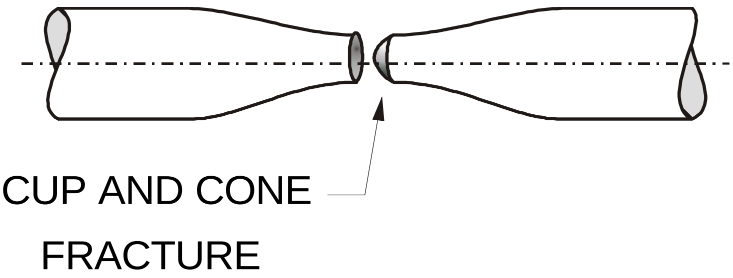
Between points 'B' and 'D' the material behaves in a plastic or ductile manner. This is known as the '**Plastic Range**'.

At **point 'C'** the maximum or ultimate tensile force that the material can withstand is reached. This is called the '**Ultimate Load**'.

Between 'C' and 'D' the cross-sectional area of the sample reduces or 'necks'.

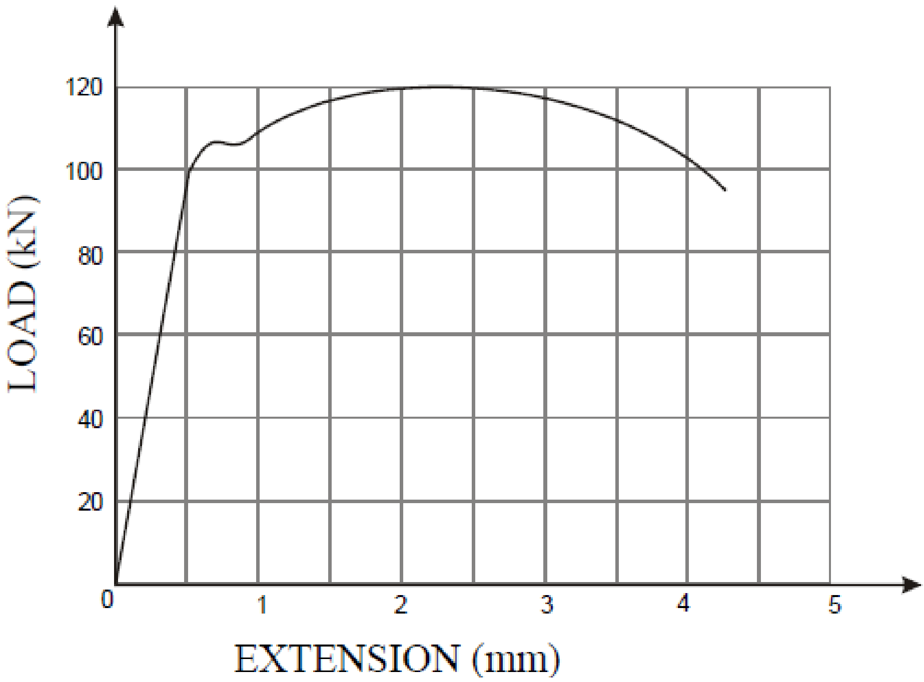


'Necking' reduces the cross-sectional area of the specimen, which in turn reduces the strength of the sample. The sample eventually reaches **point 'D'** where it breaks or fractures. This is known as the **breaking point**. The shape of a typical fractured specimen is shown below.



Task 1

The graph shown below was produced using data from a tensile test on a specimen of material.



a) Identify the following points on the graph.

- Yield point
- Elastic range
- Ultimate load
- Breaking point
- Plastic range

b) With reference to the graph, describe the effect that increasing load has on the test piece.

Task 2

A tensile test on an unknown material produced the following results.

Force kN	4.45	8.9	17.8	26.7	35.6	44.5	53.4	62.3
Extension mm	0	1.2	2.3	4.5	4.6	5.7	7.7	11

Using Graph paper, plot a graph of the load against the extension.
Attach the graph below.

Task 3

A mild steel specimen 25 mm in diameter and 250 mm long was subjected to a gradually increasing tensile load until finally the specimen snapped. The following results were obtained.

Force kN	20	40	60	80	100	120
Extension mm	0.048	0.097	0.142	0.196	0.241	0.287
Force kN	140	160	170	180	190	
Extension mm	0.343	0.39	0.42	0.46	0.52	

a) Using Graph paper, plot a graph of the load against the extension. Attach the graph below.

b) On the graph indicate two important points.

Task 4

The results from a tensile test to destruction are shown below.

Force kN	50	100	150	200	250	260	270
Extension mm	0.0007	0.0014	0.0022	0.0029	0.0036	0.004	0.005
Force kN	280	290	300	290	280	270	260
Extension mm	0.0066	0.0094	0.02	0.0238	0.0256	0.028	0.03

a) Using Graph paper, plot a graph of the load against the extension. Attach the graph below.

b) On the graph indicate three important points.

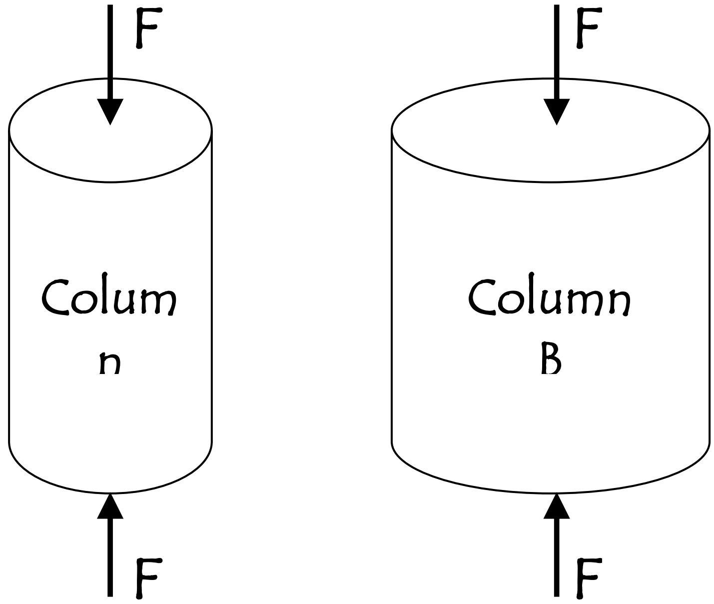
c) With reference to the graph, describe the effect of gradually increased tensile load on the specimen.

Stress Strain Graphs

Far more useful to an engineer than a load extension graph is a stress strain graph. This in many ways resembles a load extension graph but the data in this form can be interpreted more easily in design situations. First let us examine what is meant by stress and strain.

Stress

When a direct force or load is applied to the member of a structure, the effect will depend on the cross-sectional area of the member. Lets look at column 1 and 2 below. Column 2 has a greater cross-sectional area than column 1. If we apply the same load to each column, then column 1 will be more effected by the force.



The effect that the force has on a structural member or element is called STRESS. This is calculated using the formula:

Stress is calculated using the formula:

$$\text{Stress} = \frac{\text{Force}}{\text{Area}} \qquad \sigma = \frac{F}{A}$$

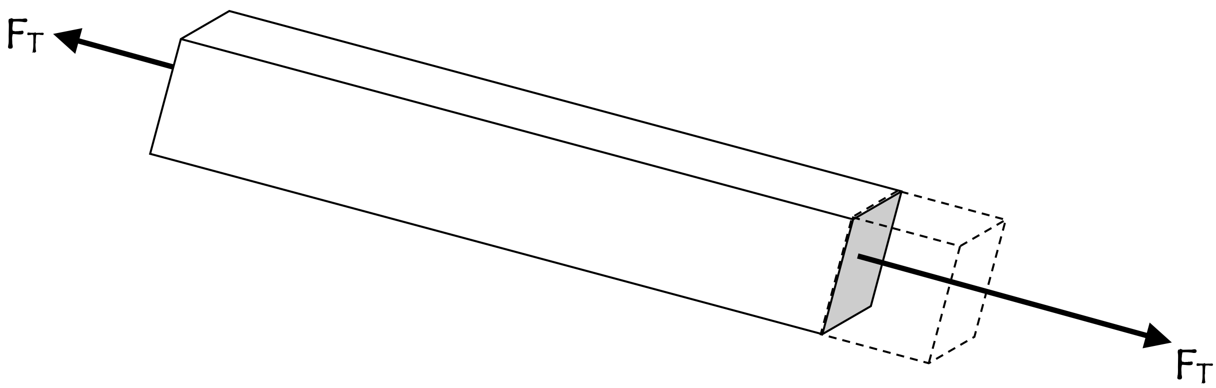
Force is measured in Newtons, Area is measured in mm^2, therefore **Stress is measured in N/mm^2**

Strain

The result of applying a load or force to a structural member is a change in length. Every material changes shape to some extent when a force is applied to it. This is sometimes difficult to see in materials such concrete and we need special equipment to detect these changes.

If a compressive load is applied to a structural member, then the length will reduce. If a tensile load is applied, then the length will increase. This is shown in the diagrams below.

The result of applying a load to a structural member is called STRAIN. This is calculated using the formula:



$$\text{Strain} = \frac{\text{Change in Length}}{\text{Original Length}} \qquad \varepsilon = \frac{\Delta L}{L}$$

The length in both parts of the equation cancel each other out. Because of this strain is dimensionless and <u>DOES NOT</u> have a unit.

Task 5

a) A square bar of 20mm x 20mm cross section is subjected to a tensile load of 500N. Calculate the stress in the bar.

b) A wire 4mm in diameter is subjected to a force of 300N. Finds the stress of the wire.

c) The stress in a steel wire supporting a load of 8kN should not exceed 200n/mm$^{2.}$ Calculate the minimum diameter of wire required to support the load.

Task 6

a) A steel wire 5m long is used to support a load. When the load is applied the wire stretches by 2.5mm. Calculate the strain of the wire.

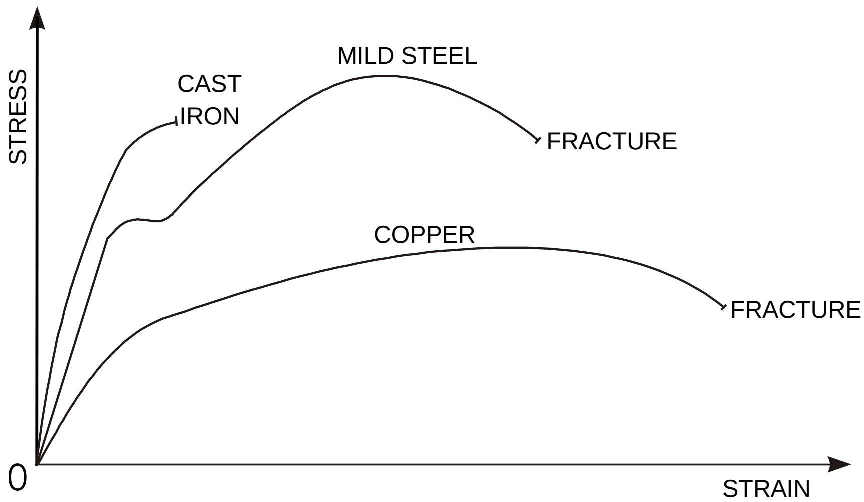
b) A wire 10m long stretches 5mm when a force is applied at one end. Calculate the strain.

c) The allowable strain on a bar is 0.0075 and its length is 2.5m. Find the change in length.

d) During testing, a steel rod stretches 0.6mm. If the resulting strain was 0.00012, what is the original length of the rod?

Using Data from Stress Strain Graphs

As we have already learned, vital information can be obtained from tensile tests when the data is plotted in the form of a stress strain graph. The graph below represents the relationship between stress and strain for common materials.



The following points are important in relation to the graph.

1. Yield Stress

The yield stress is the maximum stress that can be applied to a structural member without causing a permanent change in length. The loading on any structural member should never produce a stress that is greater than the yield stress. That is, the material should remain elastic under loading.

2. Yield Strain

The yield strain is the maximum percentage plastic extension produced in a material before it fails under loading. A ductile material such as copper needs to be formed and shaped into items such as pipes. For this to be effective, the material requires a high value of yield strain.

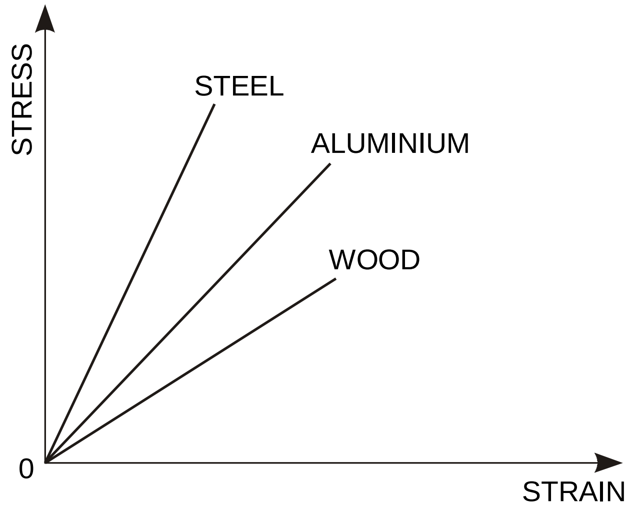
3. Ultimate Tensile Stress

The ultimate tensile stress (UTS) of a material is the maximum stress the material can withstand before it starts to fail. If a member in a structure is loaded beyond the UTS, the cross-section will reduce and the member will quickly fail.

Young's Modulus

When a material is constantly loaded past its elastic limit, its performance becomes unpredictable. This could be disastrous, even fatal, if we consider the scale and type of structures we use every day. For this reason, structural engineers must ensure that projected stresses in structural members are held within the materials elastic limit.

When we test a range of common material we find that they all behave in an elastic manner up to a certain level of loading, even very brittle materials.



We also find that within the elastic limit, the graphs are a straight line therefore conforming to Hooke's Law. This means that stress is proportional to strain. We use the principle of Hooke's Law to find a value called young's Modulus. Young's Modulus is sometimes called the Modulus of elasticity and is calculated using the formula:

$$E = \frac{\text{Stress}}{\text{Strain}} \qquad E = \frac{\sigma}{\varepsilon}$$

Young's Modulus is measured in kN/mm^2.

For any material, which obeys Hooke's Law, the slope of the straight line within the elastic limit can be used to determine young's Modulus. Although any value of stress and strain can be taken from within this region, it is customary for values to be taken from the graph at 50% of yield stress.

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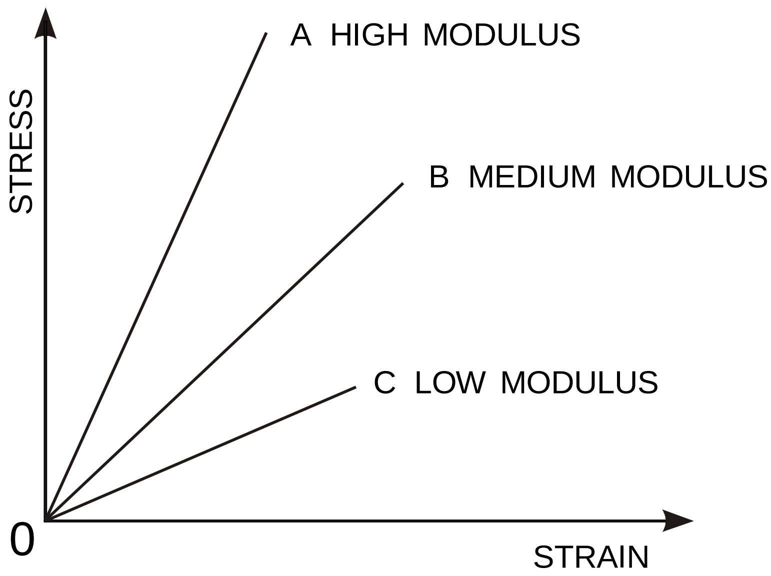
Modulus of elasticity determines the stiffness of a material. The higher the modulus, the greater the stiffness. Stiffness is a measure of a materials resistance to buckling under compressive loading. If a structural member starts to buckle it will bend and eventually collapse.

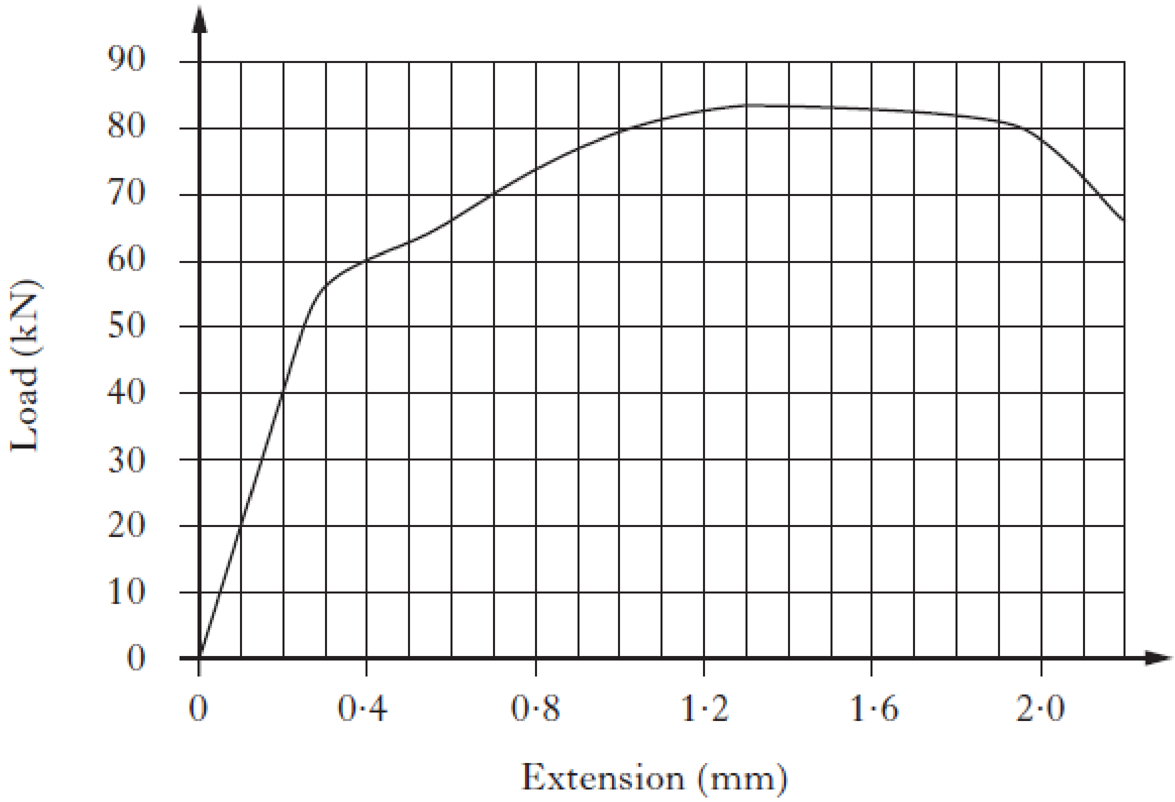


Task 7

An aluminium tie rod is 1.5 m long and has a square cross-section of 20 mm x 20 mm. A tensile load of 5.6 kN is applied and produces a change in length of the rod of 0.3 mm.
Calculate young's Modulus for the rod.

Task 8

Below shows the load-extension graph produced during a tensile test performed on an alloy-steel specimen.



The test specimen was 120 mm long with a rectangular cross-section of 26 mm × 6 mm.

a) Calculate Young's Modulus for this material.

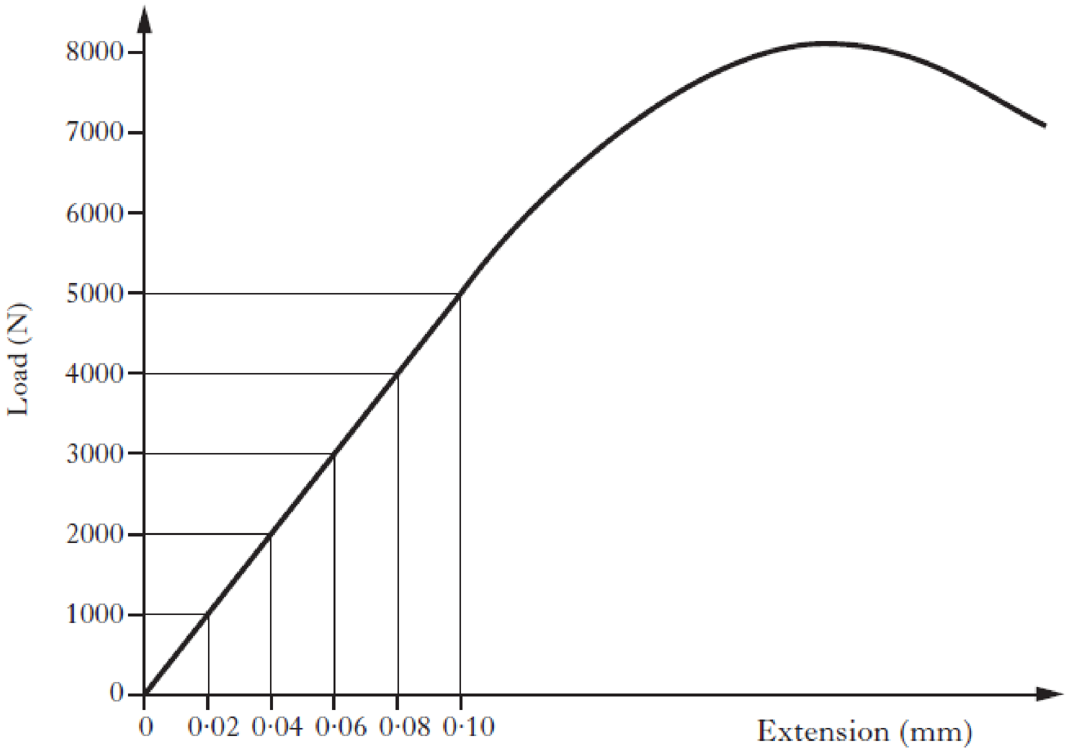
b) Describe the effect on the specimen of **applying** and then **removing** the following loads:

(i) 50 kN;

(ii) 80 kN.

Task 9

A load-extension graph for a standard test specimen is shown below. The specimen is 200 mm long and 11·3 mm in diameter.



a) Calculate Young's Modulus for the test specimen.

b) State the name of the material from which the test specimen is made.

Task 9 (Continued)

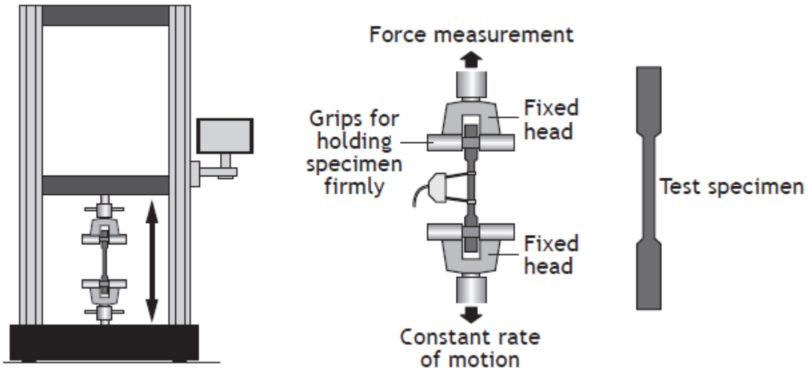
c) On the graph on the previous page, show the yield point, the ultimate load, the plastic range and the elastic range.

Two further specimens were tensile tested. The dominant mechanical property of specimen A was brittleness, and that of B was ductility.

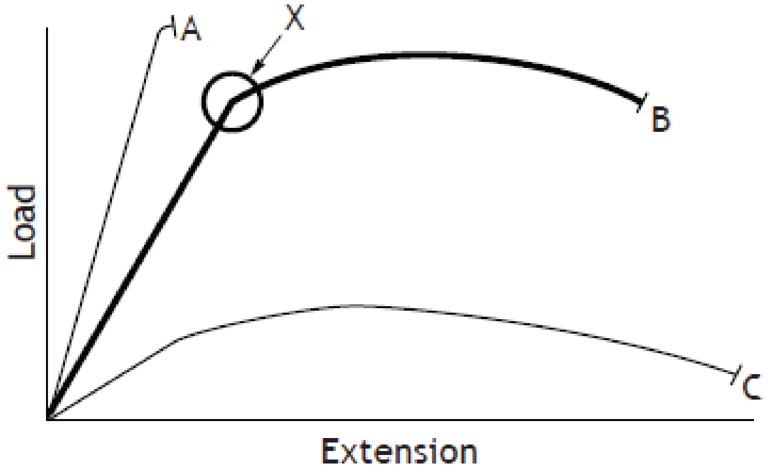
d) Sketch, on the same axes, typical stress-strain graphs for specimen A and specimen B. Clearly label the axes and identify each graph.

Task 10

A structural engineer has asked for a tensile strength test to be carried out on three metal specimens (A, B and C) using the equipment shown.



The results are displayed on the load extension graph shown below.



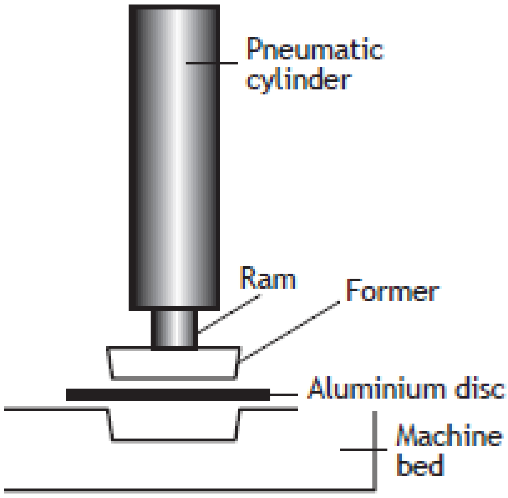
a) (i) State which of these metals has the highest value of Young's Modulus.

(ii) Describe what this means.

b) Describe, using appropriate terminology, the way in which metal B responds to loading around X.

Task 11

To make the base of a can, a pneumatic ram and former presses a disc of aluminium alloy into a suitably shaped cavity in the machine bed as shown.



Aluminium alloy is a ductile material.

a) Explain why being ductile makes the alloy suitable for this application.

The ram is made from alloy steel and applies a force of 6·0 kN to make the aluminium alloy cup. The result of this pressure is **compressive** stress which causes a small change in the length of the ram.

The ram has a diameter of 65 mm and an original length of 120 mm.

b) Calculate:

(i) The change in length of the ram during the pressing operation;

(ii) The strain energy within the ram due to this change in length.

Factor of Safety

Most structures are extremely safe and well-designed but due to unforeseen circumstances some structures fail or collapse. A structural engineer can never be absolutely certain that he/she has accounted for every possible type of load that will affect the structure. When a structure has failed, an investigation normally takes place to discover the reason for failure. The most common reasons include:

Overloading

This is when the load on the structure exceeds the value that was used during the design process. This type of failure may be due to the structure being used inappropriately, e.g. a man riding a child's bike, or because the circumstances have changed since the original design. This may be the case in bridges that were designed many years ago, where original calculations accounted mainly for cars passing over the bridge. Nowadays, we are only too aware of the increasing traffic on the road especially heavy goods vehicles. This leads to traffic jams where the traffic comes to a standstill. This may overload the structure beyond its design limit.

The most dangerous cause for a sudden change in loading on a structure is probably the weather. This is because of its unpredictable nature. No one can predict with any certainty what the weather will be like tomorrow, next week or next year. Freak weather conditions like hurricanes produce an additional force on a structure over and above what may have been calculated for a normal windy day.

Material/Joint Failure

The material within the structure may fail if it is not of consistent quality or because it has deteriorated due to the working environment of the structure. We could never guarantee the performance of natural materials such as wood as they all contain natural defects such as knots, shakes etc. Some materials are susceptible to particular conditions, for example wood swells up as it absorbs moisture, and mild steel rusts due to oxygen and water.

The joints used within the structure may fail because they are inappropriate and cannot support the load, or if they have been poorly made. This is particularly relevant with techniques such as welding. The welds on large structures are usually x-rayed in order to detect any defects.

Fatigue

It is difficult to predict exactly when a structure will fail. Repeated loading and unloading of a structure will wear down the material's resistance to breaking and eventually it will fail. This may even be the case if the load remains within the maximum used in the original design calculations. The principle of fatigue can be demonstrated by bending a paper clip backwards and forwards. The paper clip will not snap the first time, or probably the second. After that we are unsure just when the paper clip will fail. Each time we bend it we are not applying any greater a force but eventually the paper clip snaps.

Applying a Factor of Safety

Depending on the performance criteria which a structure must meet; a factor of safety will be applied to the design. Factors of safety vary from one structure to another, depending on the consequences of failure. The factor of safety applied to a nuclear power station is much higher than that for a conventional power station because the implications of structural failure are far more serious. The factors of safety applied to any design is decided through the experience and knowledge of the designer in charge, as well as close examination of the structure itself and the job it is expected to do. The higher the value for factor of safety, the more cautious the engineer is about the design.

The actual load which the structure or component is designed to carry is only one factor in a complicated process. The designer must remember certain other things such as that very high quality materials are expensive; very accurate dimensions are difficult to achieve during manufacture; quality of bolts, rivets or welds may vary; there may be very high stresses during the construction process; and so on. The following points affect the decision on the factor of safety:

1. The value of the maximum load and accuracy of calculations.

2. The type of load on the structure.

3. The reliability/quality of the material.

4. The effect of corrosion or wear on the dimensions of the structure.

5. Errors during manufacture or construction.

6. The consequences of failure.

To help with this process, the engineer might ask himself/herself the following questions:

1. What is likely to be the cause of structural failure? Have I considered every possibility even the obvious causes such as the material, shape of the structure, joining techniques?

2. What are the implications if the structure fails? What damage will be caused and what effect will this have on human life and existence?

3. What are the operating conditions of the structure like? Is this a harsh working environment in terms of weather or chemicals that may corrode the materials within the structure?

4. What external factors or conditions might affect the structure? What is the structure built upon? Is there likely to be any 'freak', one-off incidents such as a sudden impact?

5. Are there likely to be changes to any of these conditions within the working life of the structure?

In National 5 we learned that increasing the size or thickness of members within the structure, or even increasing the number of structural members would make our structure stronger. In reality though, it is possible that you would make the structure weaker and more susceptible to failure. As you make these changes, the structure will become heavier and the loading increases under its own weight. You may be solving one problem but creating another.

Calculating Factor of Safety

We can apply a factor of safety to a structure in one of two ways. The first is in terms of the loading the structure can withstand and the second is in terms of the stress within the structure.

$$\text{Factor of Safety} = \frac{\text{Ultimate Load}}{\text{Safe Working Load}}$$

$$\text{Factor of Safety} = \frac{\text{Ultimate Stress}}{\text{Safe Working Stress}}$$

If a structure is designed to support a load of say 10 kN and a factor of safety of 2 is applied to the design, then in fact the structure should be able to support 20 kN. In industrial settings such as factories, lifting devices are marked to show how much the weight can be lifted safely. This is known as the safe working load (SWL).

The loading on any structural member should never produce a stress that is greater than the yield stress of the material that the member is made from. In fact, the working stress to which a structural member will be subjected is generally well below the material's yield stress, therefore operating well within the elastic region. This ensures that if any sudden unexpectedly high loading is applied, the stress in the structural element will not exceed the yield stress preventing permanent deformation in the element. A factor of safety (FOS) of 2 means that the design is stressed to half the value at the yield point.

Accessing Tabulated Data

Most commonly used materials have been tested exhaustively and the test data is available in British Standards publications. In the course of your work in Technological Studies you will be required to use extracts from these publications in the same way an engineer might.

The table below is a copy of information provided within the SQA data booklet for use in exams.

Material	Young's Modulus E $kNmm^{-2}$	Yield stress σ_Y $kNmm^{-2}$	Ultimate tensile stress Nmm^{-2}	Ultimate compressive stress Nmm^{-2}
Mild steel	196	220	430	430
Stainless steels	190–200	286–500	760–1280	460–540
Low-alloy steels	200–207	500–1980	680–2400	680–2400
Cast iron	120	–	120–160	600–900
Aluminium alloy	70	250	300	300
Titanium alloy	110	950	1000	1000
Nickel alloys	130–234	200–1600	400–2000	400–2000
Concrete	–	–	–	60
Concrete (steel reinforced)	45–50	–	–	100
Concrete (post stressed)	–	–	–	100
Plastic, ABS polycarbonate	2·6	55	60	85
Plastic, polypropylene	0·9	19–36	33–36	70
Wood, parallel to grain	9–16	–	55–100	6–16
Wood, perpendicular to grain	0·6–1·0	–	–	2–6

For each material listed in the table, data is given on:
Young's Modulus – the elasticity or stiffness of a material.

Yield Stress – the value of stress which, if exceeded, will result in the material changing length permanently.

Ultimate Tensile Stress – the maximum value of stress the material can withstand before failing due to tension.

Ultimate Compressive Stress – the maximum value of stress the material can withstand before failing due to compression.

You will notice from the table that some materials perform quite differently in tension and compression, for example soft brass performs better in compression than tension. Other materials perform equally well under both types of loading, for example low-alloy steel and titanium alloys.

Task 12

A support wire for an outdoor suspended sign is in tension. While still in its elastic range, it extends by 0·15 mm when under a load of 717 N. The support wire has a diameter of 12 mm and a length of 2600 mm.

a) (i) Calculate Young's Modulus for the support wire.

(ii) State the name of the material used in the support wire.

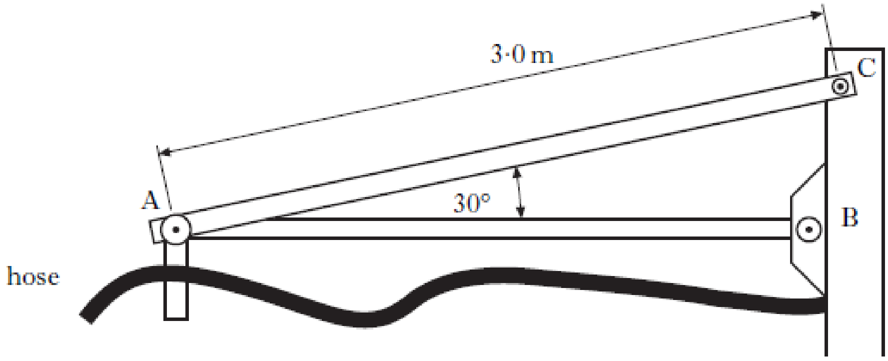
A Factor of Safety of 7 is applied to the support wire.

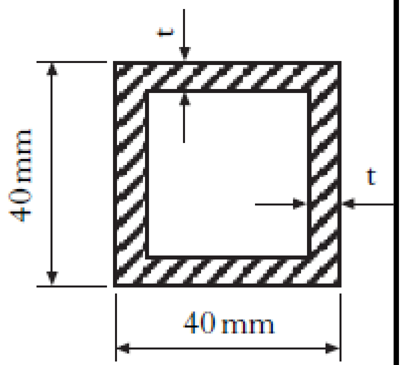
b) Calculate the maximum safe working load for the support wire.

(c) State **two** reasons for the choice of a high Factor of Safety in this application.

Task 13

A fuel hose is supported by the frame shown below





Member AC is a hollow square-section aluminium-alloy tube, as shown.

The hose exerts a vertical force of 1.2 kN on node A, and this causes a change of length in member AC of 0.91mm.

a) For member AC, calculate:

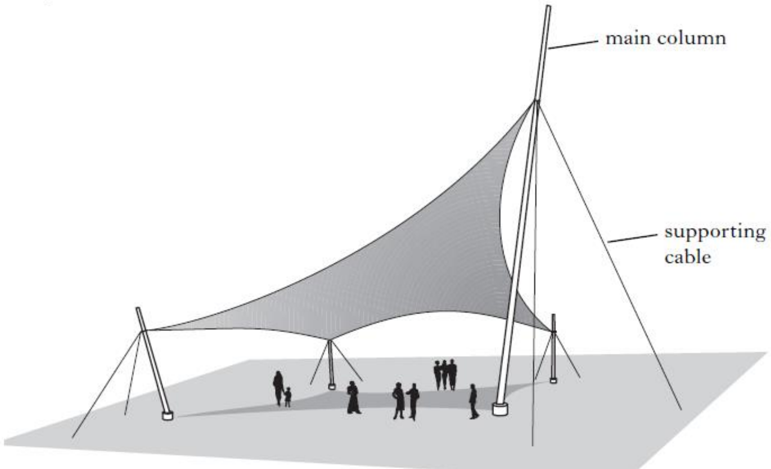
(i) The stress;

(ii) The Factor of Safety;

(iii) the material thickness (t).

Task 14

A garden centre has commissioned a design for the shade structure shown. Titanium-alloy supporting cables hold the main columns in position.



The supporting cables have an effective diameter of 10 mm and the safe working strain is 0.0009.

a) State why a high factor of safety would be appropriate for this design.

b) (i) Calculate the safe working stress.

(ii) Calculate the factor of safety.

c) Determine the maximum permissible load that can be applied to a supporting cable.