## 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, 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 designer 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?

It is easy to think that we can improve the performance of a structure by increasing the size or thickness of members within the structure, even increasing the number of structural members. In doing so however, it is possible to make the structure weaker and more susceptible to failure. As you make these changes, the structure becomes heavier and 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.

$$FactorofSafety = \frac{UltimateLoad}{SafeWorkingLoad}$$

$$FactorofSafety = \frac{UltimateStress}{SafeWorkingStress}$$

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.

**Worked example: Factor of Safety**

The maximum ultimate tensile stress for aluminium is 300 N/mm$^2$. If the working stress on a component is 50 N/mm$^2$, calculate the factor of safety applied in the design of the component.

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

$$Factor\,of\,Safety = \frac{300}{50}$$

$$Factor\,of\,Safety = 6$$

## 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 $kN/mm^2$ | Yield Stress $N/mm^2$ | Ultimate Tensile Stress $N/mm^2$ | Ultimate Compressive Stress $N/mm^2$ |
|---|---|---|---|---|
| Mild Steel | 196 | 220 | 430 | 430 |
| Stainless Steel | 190-200 | 286-500 | 760-1280 | 460-540 |
| Low-alloy steel | 200-207 | 500-1980 | 680-2400 | 680-2400 |
| Cast iron | 120 | - | 120-160 | 600-900 |
| Aluminium alloy | 70 | 250 | 300 | 300 |
| Soft Brass | 100 | 50 | 80 | 280 |
| Cast Bronze | 120 | 150 | 300 | - |
| Titanium alloy | 110 | 950 | 1000 | 1000 |
| Nickel alloys | 130-234 | 200-1600 | 400-2000 | 400-2000 |
| Concrete (steel reinforced) | 45-50 | - | - | 100 |

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.

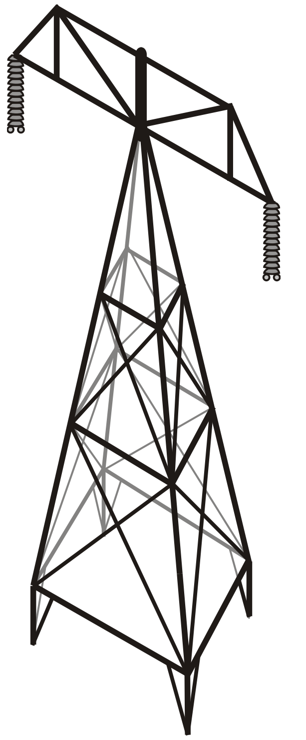
Ultimate Tensile Stress - the maximum value of stress the material can withstand before failing due to tension.

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

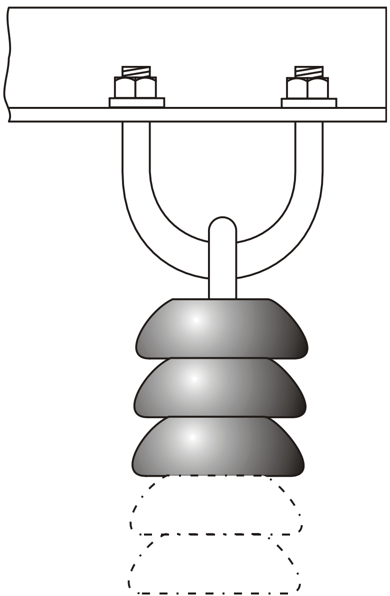
You will notice from the table that some materials perform quite differently in tension and compression, for example soft brass performs better in compression than tension. Other materials perform equally well under both types of loading, for example low-alloy steel and titanium alloys.

**Assignments: Tabulated Data**

1. Figure 1 shows a general view of an electricity pylon. The cross-arm supports conductor wires by means of an insulator suspended from its end. The insulator is fixed to the pylon by means of a low-alloy U-bolt shown in figure 2. Explain why a high factor of safety is required for this particular application. Suggest ways in which the structure might fail.



SM H O.4 fig1



SM H O.4 fig2

2. A lighting gantry in a theatre is suspended from the ceiling by wire ropes. The gantry hangs above the audience and is designed to hold 10 lights. A factor of safety of 10 is applied to the design. Explain the reasons why the engineer has used such a high factor.

3. In an Art Gallery, a sphere weighing 10 kN is to be suspended from the ceiling by a stainless steel bar 20 mm in diameter and 3 m long.

Select a value for Young's Modulus for Stainless Steel and hence calculate the extension of the bar when loaded. State any assumptions made.

If a factor of safety of 5 was applied to the design, discuss the effect of this on the dimensions of the bar. (Use the Data Booklet.)

4. A soft brass bar, which is used in a structure, is 120 mm long. It is subjected to a tensile load that elongates its original length by 0.03 mm.
   Determine the factor of safety employed in the design of this bar. (Use the Data Booklet.)

5. A steel overhead wire 25 mm in diameter has an ultimate tensile stress of 1250 $N/mm^2$ and a value for Young's Modulus of 207 $kN/mm^2$. If the factor of safety is 5, calculate the allowable pull on the wire and find the corresponding change in length on a 36 m span.

6. The maximum load in a tensile test on a mild steel specimen is 76 kN. If the test piece is 15 mm in diameter, calculate the ultimate tensile stress. What is the working stress and greatest allowable load on a bar 30 mm in diameter made from the same material? Use a factor of safety of 3.

7. A tensile test on a specimen of an unknown material provided the following data:

Cross-sectional area = 120 $mm^2$
Gauge (original) length = 75 mm
Load (within elastic limit) = 30 kN
Extension of gauge length = 0.17 mm

a) Determine Young's Modulus of the material.

b) By referring to the Data Booklet, suggest which material was being tested.

c) Calculate the factor of safety for this material for the conditions described by the data given above.

8. A stainless steel tie-bar in a structure is to be designed to carry a load of 450 kN, with a factor of safety of 4.

   a) Explain why this material is suitable for a use as a tie but not a strut.

   b) Calculate the diameter of the bar.

   c) Calculate the amount the tie-bar will stretch if its original length is 3.5 m.

9. A mild steel bar 25 mm in diameter and 0.5 m long is held in tension as it supports a sign above a shop. Find the safe load that can be supported by the bar if a factor of safety of 8 is applied to the design. Find the extension in the bar under this load.

Describe ways in which the bar might fail given these conditions.

10. A trapeze wire is made from a material for which the ultimate tensile stress is 1000 $N/mm^2$ and the yield stress is 950 $N/mm^2$. The wire has a working load of 3 kN.

    a) Calculate the factor of safety to keep the stress just within the elastic limit for the material.

    b) Calculate the diameter of the wire for this factor of safety.

    c) Calculate the diameter of the wire for a factor of safety of 3.

    d) Which factor of safety would you apply to this design? Explain your answer.

11. Winches are used on aircraft carriers to haul helicopters across the landing deck. The winch cables are made from mild steel and are fixed to the helicopter landing gear. The tension in the cables is 20 kN and a factor of safety of 8 is applied to the design. Calculate the diameter of the cable.

12. A single mild steel cable supports a lift. The safe working load of the lift is 30 kN and a factor of safety of 12 is applied to the cabling. If the length of the cable is 100 m and the allowable extension is 50 mm, calculate the required diameter of the cable. Explain why such a high factor of safety has been applied in this design. Suggest one way to improve the design of this system.

13. If the ultimate tensile stress of a steel wire is 750 $N/mm^2$, what load could safely be carried by the wire of diameter 2.5 mm? Use a factor of safety of 5. If the wire is 6 m long and the extension is 4.8 mm, what is the value of Young's Modulus?

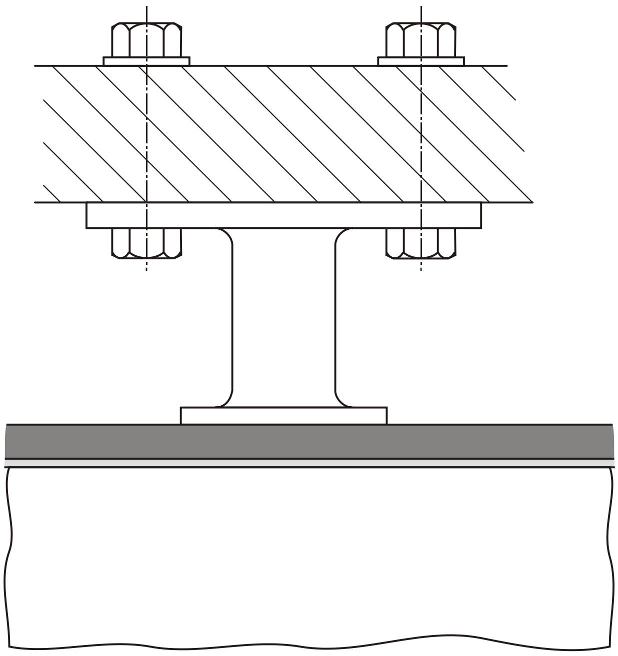
14. A lifting jack has a maximum lift of 300 mm and the diameter of the ram is 75 mm. Find the maximum force the jack may exert if the ram has to have a factor of safety of 7 and the ultimate tensile stress of the metal is 483 $N/mm^2$. Find the change in length of the ram if the modulus of elasticity of the material is 201 $kN/mm^2$.

15. A tension member in a roof truss is subjected to a pull of 117 kN. The material has an ultimate tensile stress of 465 $N/mm^2$. When a factor of safety of 5 is used, find the diameter of the member. If the member is 3 m long and stretches 1.35 mm under loading, calculate the modulus of elasticity.

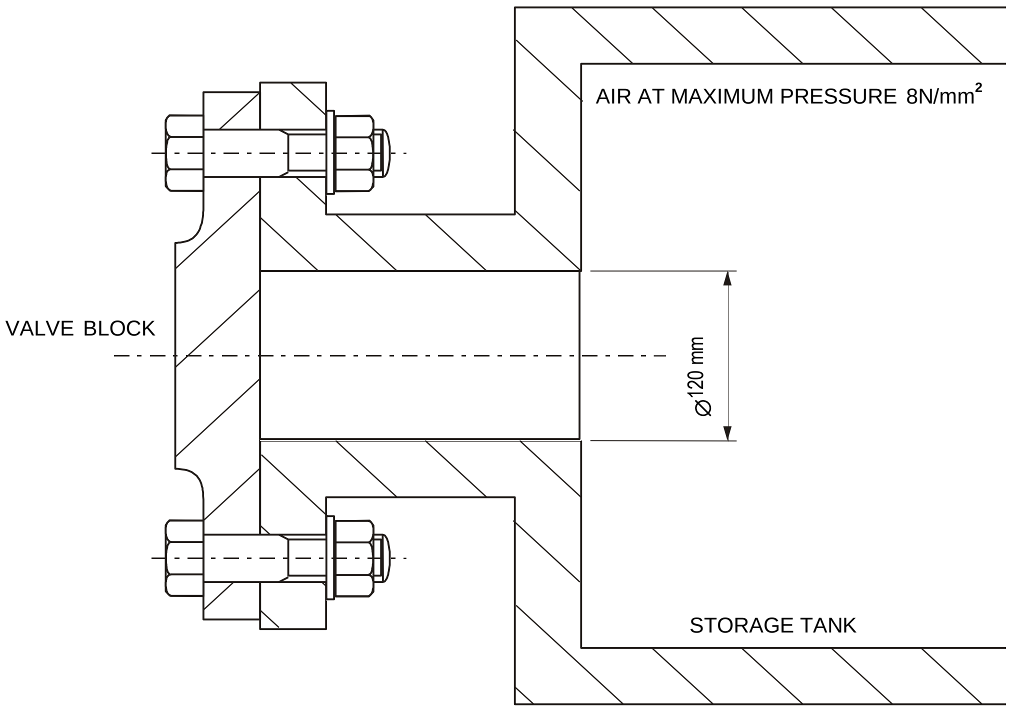
16. A display screen in a lecture theatre is held in place by a bracket fixed to the roof by two mild steel bolts as shown in figure 3. The bolts are initially tightened so that the tensile stress in them is 7 $N/mm^2$ before any load is applied.

The weight of the screen is 3 kN and the bolts carry an equal share of this load. The bolts are designed with a factor of safety of 9.

Determine the diameter of the bolts needed for this application.



17. Part of a pneumatic system is shown in figure 4. Compressed air is stored in the tank at a maximum pressure of 8 $N/mm^2$ and the 120 mm diameter outlet is sealed by means of a valve block which is held in place using 15 mm (M15) diameter bolts as shown. The normal stress set up in each bolt due to tightening is 6 $N/mm^2$ and the ultimate tensile stress for the bolts is 370 $N/mm^2$. The factor of safety for the system is 5.




a) Calculate the force on the value block using the formula, Force = Pressure x Area.

b) Calculate the safe working stress that can be carried by the bolts.

c) Calculate the stress in each bolt due to loading.

d) Calculate the load to be carried by each bolt.

e) Determine how many bolts are required to attach the valve block to the storage tank.