

Unit 11

Structural components

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Aims

- To introduce the different structural components and different types of failure.
- To show how to estimate failure forces and stresses in simple cases.

Objectives

After working through this Unit you should be able to:

- Identify different types of structural member and their loading properties (SAQs 1, 2; Sections 1.1 to 1.3).
- Design acceptable ties (SAQs 3, 4; Section 2).
- Determine beam support reactions (SAQ 5; Section 3.1).
- Determine stress and strain distributions within beams (SAQs 6, 7, 8; Section 3.2).
- Design suitable beam cross-section shapes (SAQs 9–15; Section 3.2).
- Determine bending-moment distributions within beams and analyse consequent bending stresses (SAQs 16–25; Section 3.3).
- Design compressive members to resist buckling (SAQs 26–30; Section 4).
- Design suitable circular shafts to carry torsional loads (SAQ 31–37; Section 5).

Introduction

In Block 1, Geometry of Mechanisms, you learned how an assembly of bodies could be connected for the purpose of transmitting motion in a specified manner. It is possible to connect bodies such that motion is prevented even under the influence of large loads (forces and moments). Such an assembly is a *structure* and we can regard it as an assembly of members designed to resist or carry the loads safely.

structure

A structure can fail in three ways. It may break, it may deform too much or it may become unstable and suddenly collapse. A successful structure is sufficiently well endowed with the three 'S's — Strength, Stiffness and Stability, under the applied loads.

In a structure under load various individual loads are generated in the constituent bodies (or members) themselves, and they are each subject to stresses and strains. Whilst in the study of Kinematics we considered each member as a rigid body, we cannot do that in the design of structures. The deformations of the members, although usually very small, are highly significant in terms of the analysis of stress and strain of the members and the overall performance of the structure. Depending on how the loads are applied within the structure an individual member can be classified as one of four types. Sometimes a single member acts as more than one type at the same time.

In this Unit I will start by defining the three properties of a structure, and then consider the four different types of structural member. I will define safety criteria related to working loads and stresses and, in turn, consider the design of the four types of individual member, in terms of acceptable loads, stresses and strains. As in Unit 10, for the purposes of analysis I shall limit my materials to those which can be considered uniform throughout — i.e. linear, elastic, homogeneous and isotropic at all points (Unit 10, Section 2.2).

1 Structures and their components

1.1 Structural properties

A structure as a whole, and each individual member, must be designed with reference to the three 'S's: strength, stiffness and stability:

strength

Strength is the ability to carry the applied loads without yielding or breaking. Examples of strength failures are a cable which snaps, a vehicle body which crumples, and a glass panel being smashed.

stiffness

Stiffness is the ability to carry the applied loads without too much distortion. A material can only sustain stress at the expense of some strain ($\sigma = E\epsilon$). Sometimes the strain, even though very small, may be the limiting factor. For example, a machine tool must be stiff enough to produce the required accuracy in machining, and a camera tripod must be stiff enough to prevent camera shake.

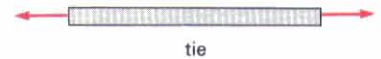
stability

Stability is the ability to carry compressive loads without collapsing or buckling out of shape. For example, a metal rod in compression longitudinally will suddenly bow out of shape under a compressive stress which is well below the compressive yield stress.

1.2 Types of structural member

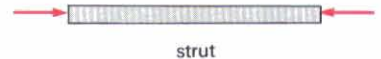
The importance of the different types of failure, in considering any particular member, depends on how the loads are applied to it. In fact the members are categorized according to the way in which the forces are applied (Figure 1).

Tie: a member in tension



tie

Strut: a member in compression
(vertical struts are also called columns or stanchions)



strut

Beam: a member with loads that cause bending



beam

Shaft: a member in torsion (twisting)



shaft

Figure 1

These four types of loading define the four structural components: ties, struts, beams and shafts. Real members often carry a combination of loads.

Figure 2 shows a suspension bridge, and Figure 3 a breakdown into parts. The roadway or 'deck' hangs from the vertical cables, which must be in tension. In turn they hang from the main suspension cables which are also in tension. These main suspension cables are anchored at their ends, and pull down on the towers, putting the towers into compression. The deck,



Figure 2

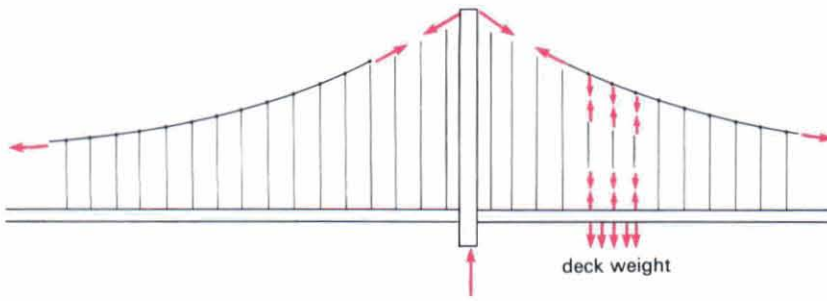


Figure 3

supported by the vertical cables, and carrying the various traffic loads, is in bending, although it can be subject to torsion as well due to asymmetric traffic loads and wind forces on the cables. A suspension bridge therefore contains the four types of component.

1.3 Failure and safety factors

Table 1 shows the four general types of structural component and the three types of failure. Note that a tie is pulled straight by the tension, so it cannot suffer stability failure. The stability of beams and shafts is difficult to analyse and anyway is not usually the limiting factor, so in this course we shall only deal with stability of struts. Strength failures of all the components types are possible, and you have already studied direct tension and compression in Unit 10. In this Unit you will also be looking at the strength of beams and shafts. Finally, the stiffness of all the components, i.e. their deflections under moderate load, can be important. In one Unit you cannot cover all these, so I have excluded beam deflections.

Table 1 Topics covered in Unit 11

Failure type	Component type			
	TIE (tension)	STRUT (compression)	BEAM (bending)	SHAFT (torsion)
Strength	✓	✓	✓	✓
Stiffness	✓	✓	×	✓
Stability	Not Applicable	✓	×	×

At this stage you should ensure that you are familiar with the following terms, which apply to all types of structural member:

Safe working load (SWL) The load which is considered safe, and therefore the load up to which a component may be properly used.

safe working load

Calculated failure load (CFL) The load which is estimated by calculation to just cause failure under a single application.

calculated failure load

Stress safety factor (SSF) The factor by which the calculated stress could be increased before reaching a chosen limit (e.g. σ_Y or σ_F or τ_Y according to material data):

stress safety factor

$$SSF = \frac{\sigma_Y}{\sigma} \quad \text{or} \quad \frac{\sigma_F}{\sigma} \quad \text{or} \quad \frac{\tau_Y}{\tau}$$

Load safety factor (LSF) The factor by which the load could be increased before reaching the calculated load limit.

load safety factor

Please note that the actual load that will cause failure is *not* the CFL. The calculated failure load is a theoretical value and is only an approximation to the real value, which may never be known. The safety factor is therefore also a theoretical value. A structure with a safety factor of two may fall down, because the theory was in error by a factor worse than two. The older and wiser an engineer gets, the more things cause worry, and the bigger the safety factor becomes! The actual failure load is never really known whilst the structure remains in one piece. A structure that meets its specification is a success, but a structure that fails is at least a chance to learn.

SAQ 1

A workshop lifting gear is required to lift 1000 kg. Calculate the minimum wire failure tension permissible for a LSF of 10.

SAQ 2

A lift has a 'cabin' of mass 2000 kg and is permitted to carry 1500 kg mass. The supporting wire has a failure tension of 500 kN. Estimate the load safety factor.

If stress is the limiting factor, as in ties, then the SSF and the LSF will be equal. However, for struts they are not normally equal. Struts can fail by collapsing under quite low stresses, and in that case the load safety factor is much smaller than the stress safety factor and so is the more important.

2 Ties

tie

A *tie* is a member in tension, typical examples being a car tow rope or hoist cable. A rope or cable is flexible — it bends and twists easily. This is not detrimental to its operation as a tension member because it pulls straight automatically. The flexibility may be a great advantage as the rope or cable can be wound on to a drum or coiled up for storage. Alternatively a tie may be rigid and in some cases is not obviously different from a strut. In fact, one member may be called upon to do both jobs at different times. The largest ties that I know of are the main cables of suspension bridges.

You have already done some calculations on tension members in the stress analysis unit (Unit 10). The average tensile stress is $\sigma = F/A$, and this can be compared with the chosen limit stress of the material, σ_Y or σ_F , to find the stress safety factor. Alternatively, the limit stress times the area gives the limit load which, divided by the load, gives the load safety factor. For a tension member the two safety factors are equal, but this is not true for struts because of the stability problem. Even so, tension members usually have quite large safety factors, because of the stress-raising effects of end connections, bending around pulleys, handling damage, sensitivity to cracks, and so on.

Under moderate load a tie extends approximately according to $F/A = Ee/L$, as you saw in Unit 10. In a few special cases this stretching may be excessive even if the strength safety factor is adequate. This would of course be a stiffness failure, in which case the cross-sectional area could be increased or a stiffer material used. Here is one possible procedure for tie design checking: