optimized with regard to this condition. In some engineering structures and in very many biological ones, however, the load may come from any direction. This is roughly true for lamp-posts, chair legs, bamboos and leg-bones. For such purposes it is better to use a round, hollow tube, and of course this is what is very often done. An intermediate case occurs with bermuda masts. These are generally made from tubes of oval or pear-shaped section. This is not primarily so as to reduce wind-drag by 'streamlining', as is often supposed, but rather to cater for the fact that it is much easier to stay a modern mast laterally than it is in the fore and aft plane, and so the mast section has to take account of this by providing more strength and stiffness fore and aft.

Chapter 12 The mysteries of shear and torsion

– or Polaris and the bias-cut nightie

Twist ye, twine ye! even so
Mingle shades of joy and woe,
Hope and fear, and peace and strife,
In the thread of human life.

Sir Walter Scott, *Guy Mannering*

There is supposed to have been a book review by Dorothy Parker which started off 'This book tells me more than I care to know about the Principles of Accountancy'. And indeed I dare say that many of us are apt to come to the conclusion that the way in which things behave in shear might, after all, be left to the experts. Tension and compression we feel we can cope with, but when it comes to shear we think we can detect a tendency for the mind to boggle.

It is unfortunate, therefore, that the shear stresses to which we are introduced in the elasticity text-books are assumed to spend their time inhabiting things like crankshafts or the more boring sorts of beams. Though undeniably worthy, this approach somehow lacks human appeal, and it also diverts attention from the fact that shearing stresses and shearing strains are by no means confined to beams and crankshafts but keep intruding into practically everything we do – sometimes with unexpected results. This is why boats leak, tables wobble and clothes bulge in the wrong places. Not only engineers, but also biologists and surgeons and dressmakers and amateur carpenters and the people who make loose covers for chairs would live better and more fruitful lives if they could only look a shear stress between the eyes without flinching.

If tension is about pulling and compression is about pushing, then shear is about sliding. In other words, a shear stress measures the tendency for one part of a solid to slide past the next bit: the sort of thing which happens when you throw a pack of cards on the table or jerk the rug from under someone's feet. It also nearly always occurs when anything is twisted, such as one's ankle or the driving shaft of a car or any other piece of machinery. Materials which are being sheared or twisted usually behave in quite straightforward and rational ways, but, rather naturally, when we come to discuss this behaviour it helps a good deal to make use of the appropriate vocabulary. So we might begin with a few definitions.

The vocabulary of shear

The elasticity of shear is very much like the elasticity of tension and compression, and concepts like shear stress, shear strain and shear modulus are pretty closely analogous to their tensile equivalents and certainly no harder to understand.

SHEAR STRESS – N

As we have said, a shear stress is a measure of the tendency for one part of a solid to slide past the neighbouring part, very much

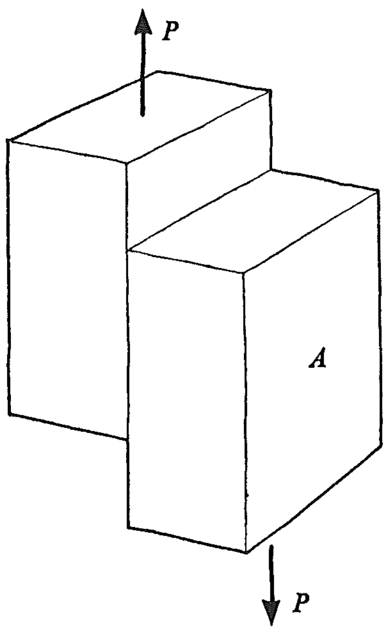


Figure 1. Shear stress $= \dfrac{\text{shearing load}}{\text{area being sheared}} = \dfrac{P}{A} = N$

as in Figure 1. Hence, if a cross-section of material, having an area A, is acted upon by a shearing force P, then the shear stress in the material at that point will be

$$\text{shear stress} = \frac{\text{shearing load}}{\text{area being sheared}} = \frac{P}{A} = N, \text{ let us say}$$

– just like a tensile stress. The units are also the same as those of a tensile stress, that is to say, p.s.i., MN/m^2 or what you fancy.

SHEAR STRAIN – g

All solids yield or strain under the action of a shear stress, in the same sort of way as they do under a tensile stress. In the case of shear, however, the strain is an angular one, and it is therefore

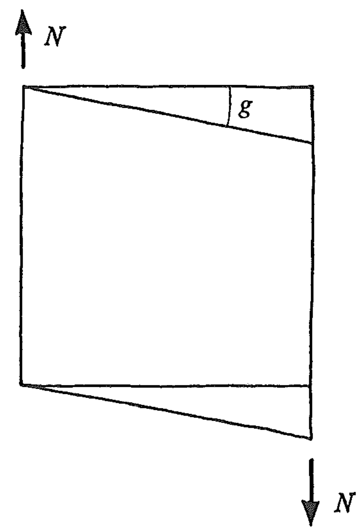


Figure 2. Shear strain = angle through which material is distorted as a result of shear stress N
= g, which is an *angle* – usually in radians.

measured, like any other angle, in degrees or in radians – usually in radians (Figure 2). Radians, of course, have no dimensions, being really a number or a fraction or a ratio. We shall call the shear strain g in this book: like the tensile strain, e, therefore, g is a dimensionless number or fraction and has no units.

In hard solids like metal or concrete or bone, the elastic shearing strain is likely to be less than 1° (1/57 radian). Beyond this shearing strain, materials of this kind will generally either break or else flow in a plastic and irrecoverable way, like butter. However, with materials like rubber or textiles or biological soft tissues, recoverable or elastic shear strains may be much higher than this – perhaps 30° to 40°. With liquids and squidgy things like treacle or custard or plasticine, the shear strain is unlimited; but then it is not recoverable.

THE SHEAR MODULUS OR MODULUS OF RIGIDITY – G

At small and moderate stresses most solids obey Hooke's law in shear, much as they do in tension. Thus, if we plot the shear stress, N, against the shear strain, g, we shall get a stress-strain curve which is, at least initially, a straight line (Figure 3). The slope or

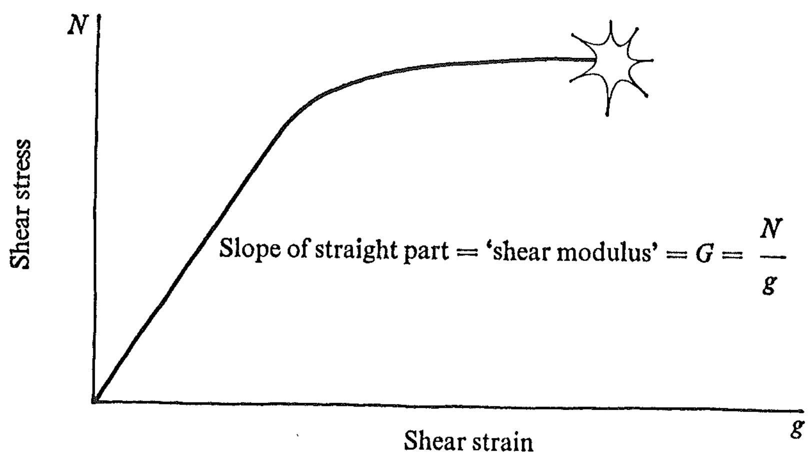


Figure 3. The stress-strain diagram in shear is very like that in tension. The slope of the straight part is equivalent to the shear modulus

$$G = \frac{N}{g}$$

gradient of the straight part represents the stiffness of the material in shear and is called the 'shear modulus', or sometimes the 'modulus of rigidity', or 'G'. Thus

$$\text{shear modulus} = \frac{\text{shear stress}}{\text{shear strain}} = \frac{N}{g} = G^*$$

So G is the exact analogue of the Young's modulus, E, and, like E, it has the dimensions and units of a stress: that is to say, p.s.i., MN/m² or whatever.

Shear webs – isotropic and anisotropic materials

As we said in the last chapter, although there may be large horizontal tension and compression forces in the top and bottom flanges of a beam or a truss, the actual upward thrust which really enables the structure to do its job of sustaining a downward load has to be produced by the web – that is to say, by the part in the middle which joins the top and bottom booms together. In a continuous beam the web will be of solid material, perhaps a metal plate; in a truss the same function will be served by some sort of lattice or trellis.

Since the distinction between a material and a structure is never very clearly defined, it does not matter very much whether the shearing loads in a beam are carried by a continuous plate web or whether they are carried by a lattice which might be made up of rods and wires, strips of wood or whatever. There is, however, an important difference. If the web is made from, say, a metal plate, then it is of no consequence in which direction the plate is put on. That is to say, if we cut the plate for the web out of some larger sheet of metal, it does not matter at what angle we cut it, since the metal has the same properties in every direction within itself. Such materials, which include the metals, brick, concrete, glass and most kinds of stone, are called 'isotropic', which is Greek for 'the same in all directions'. The fact that metals are isotropic (or nearly so) and have the same properties in

* Note that there is a relationship between G and E. For isotropic materials like metals

$$G = \frac{E}{2(1+q)}$$

where q = Poisson's ratio.

all directions makes life somewhat easier for engineers and is one of the reasons why they like metal.

However, if we now consider the lattice web, it is clear that it must be constructed so that the rods and tie-bars lie nearly at $\pm 45°$ to the length of the beam. If this is not done, then the web will have little or no stiffness in shear (Figures 4–5). Under load the lattice will fold up and the beam will probably collapse. Materials of this kind are called 'anisotropic', or sometimes

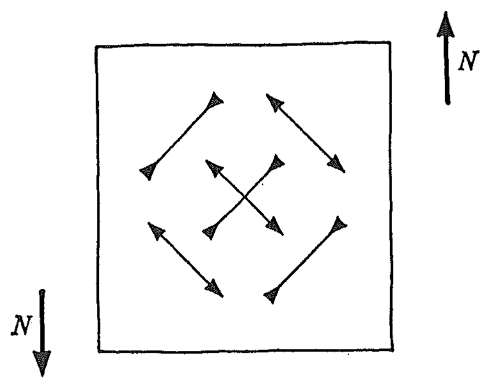


Figure 4. Shear will produce tension and compression stresses in directions at 45° to the plane of shearing.

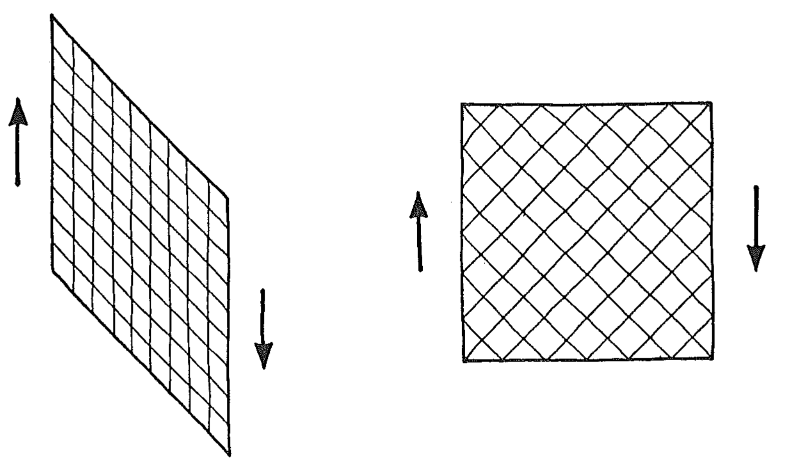


Figure 5. Thus a system like the one on the right is 'rigid' in shear, and systems like the one on the left are floppy.

'aelotropic' – both of which are Greek for 'different in different directions'. In their different ways wood and cloth and nearly all biological materials are anisotropic and they tend to make life complicated, not only for engineers, but for a great many other people as well.

Cloth is one of the commonest of all artificial materials and it is highly anisotropic. As we have said repeatedly, the distinction between a material and a structure is a vague one, and cloth, though called 'material' by dressmakers, is really a structure, made up of separate yarns or threads crossing each other at right angles; and its behaviour under load is much the same as that of the trellis web of a beam or a truss.

If you take a square of ordinary cloth in your hands – a handkerchief might do – it is easy to see that the way in which it deforms under a tensile load depends markedly upon the direction in which you pull it. If you pull, fairly precisely, along either the warp or the weft threads,* the cloth will extend very little; in

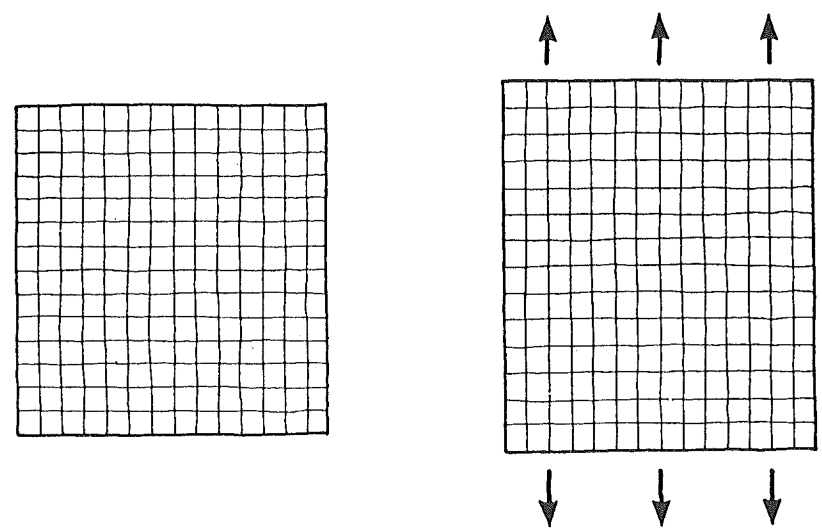


Figure 6. When cloth is pulled parallel to the warp or the weft threads, the 'material' is 'stiff' and the lateral contraction is quite small.

*Warp threads or yarns are those which run parallel to the length of a roll of cloth; weft threads are those which run across the cloth, at right angles to its length.

other words, it is stiff in tension. Furthermore, in this case, if one looks carefully, one can see that there is not much lateral contraction as a result of the pull (Figure 6). Thus the Poisson's ratio (which we discussed in Chapter 8 in connection with arteries) is low.

However, if you now pull the cloth at 45° to the direction of the threads – as a dressmaker would say, 'in the bias direction' – it is much more extensible; that is to say, Young's modulus in tension is low. This time, though, there is a large lateral contraction, so

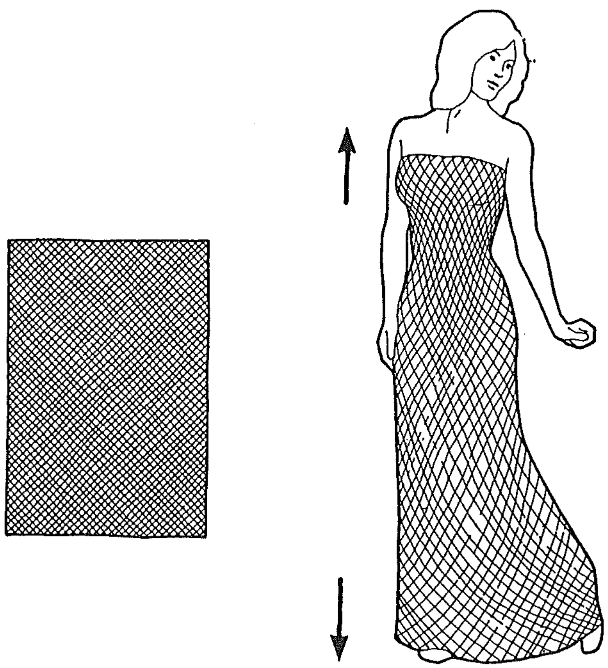


Figure 7. If cloth is pulled 'on the bias' or at ±45° to the warp and weft, the 'material' is extensible, and the Poisson's ratio – and hence the lateral contraction – is large. This is the basis of the 'bias cut' in dressmaking.

that, in this direction, the Poisson's ratio is high; in fact it may have a value of about 1·0 (Figure 7). On the whole, the more loosely the cloth is woven, the greater is likely to be the difference between its behaviour in the bias and in the warp and weft or 'square' direction.

Although I suppose that not very many people have ever heard of the word 'anisotropy', the fact that cloth behaves in this sort of way must have been familiar to nearly everybody for centuries. Rather surprisingly, however, the technical and social consequences of the anisotropy of woven cloth do not seem to have been properly realized or exploited until quite recent times.

When we stop to think about the matter, it is clear that when we make anything from cloth or canvas, we can minimize the distortions by arranging for the important stresses to run, as far as possible, along the directions of the warp and weft threads. This usually involves cutting the material 'on the square'. If the circumstances are such that the cloth is pulled at 45°, that is to say 'on the bias', then we shall get much larger distortions, which will, however, be symmetrical. But, should we be so inept that the cloth ends up by being pulled in some intermediate direction, which is neither one thing nor the other, then we shall not only get large distortions, but these will be highly asymmetrical. Thus the cloth will pull into some weird and almost certainly unwelcome shape.*

Although sailmaking has been an important industry ever since the beginning of history, these elementary facts about canvas never fully dawned upon European sailmakers. They continued from age to age to construct sails in such a way that the pull came obliquely upon both the warp and weft threads. As a consequence, their sails quickly became baggy and could seldom be made to set properly when the wind was ahead. The situation was worsened by the European predilection for making sails from flax canvas, which distorts particularly easily because of its loose weave.

Rational modern sailmaking began in the United States early in the nineteenth century. American sailmakers used tightly woven cotton canvas, and they arranged their seams in such a way that the direction of the threads corresponded more nearly to the direction of the applied stresses. Although the consequence was that American ships could frequently sail faster and also closer to

* An understanding of this principle is very important when making things like balloons and pneumatic dinghies from rubberized fabric. If shear distortions are incurred the rubber coating is strained in such a way that the fabric will leak.

the wind than British ones, it required something like an earthquake to bring the facts home to English sailmakers. This was provided by the publicity associated with the schooner yacht *America*, which came over from New York to Cowes in 1851 to compete with the fastest English yachts. She was entered for a race round the Isle of Wight which was to be sailed for a rather ugly piece of silverware presented by Queen Victoria. This jug-like object has since acquired a certain fame as the 'America's

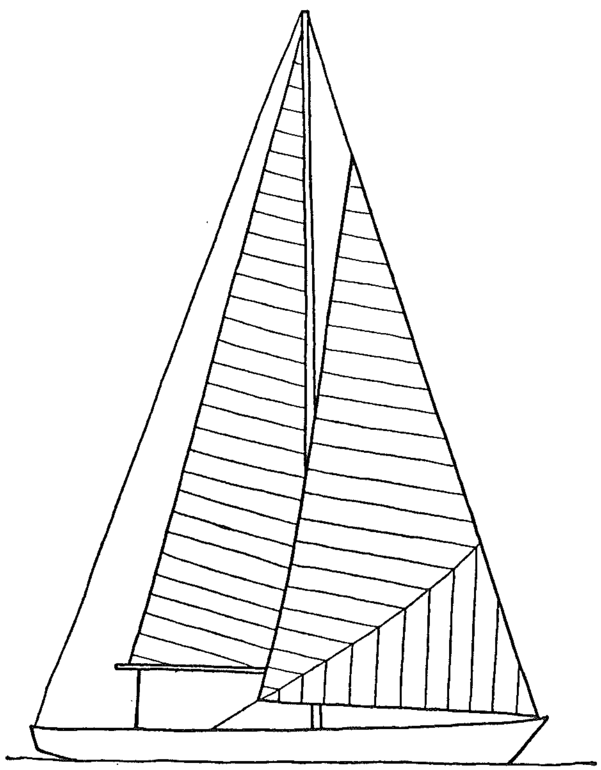


Figure 8. In modern sailmaking it is usual to arrange the weft threads of the canvas so that they are parallel to the free edges of the sail.

Cup'. When the Queen was told that the *America* was the first yacht to have crossed the finishing line, she asked 'And who is second?'

'There is no second in sight yet, your majesty.'

After this, the English sailmakers mended their ways – so much so that, within a few years, American yachtsmen would be buying their sails from Mr Ratsey of Cowes. The lessons taught by the American sailmakers have stuck, and, although the majority of modern sails are made from Terylene, not cotton, if you look at any modern sail (Figure 8) you can see that it is cut in such a way that the weft threads are, as far as possible, parallel to the free edges of the sail, which is usually the direction of greatest stress.

In many respects the problems of persuading cloth to conform to a desired three-dimensional shape are not very different in sailmaking and in dressmaking. However, tailors and dressmakers seem to have been more intelligent about the matter than sailmakers. As far as was practicable they cut their cloth on the square, so that most of the circumferential or hoop stresses came directly along the line of the yarns. When a close fit was wanted it was achieved by what might be described as a system of Applied Tension: in other words, by lacing. At times the Victorian young lady seems to have had nearly as much rigging as a sailing ship.

With the virtual abandonment of systems of lacing in post-Edwardian times – possibly on account of a shortage of ladies' maids – women might well have had to face a shapeless future. However, in 1922 a dressmaker called Mlle Vionnet set up shop in Paris and proceeded to invent the 'bias cut'. Mlle Vionnet had probably never heard of her distinguished compatriot S. D. Poisson – still less of his ratio – but she realized intuitively that there are more ways of getting a fit than by pulling on strings or straining at hooks and eyes. The cloth of a dress is subject to vertical tensile stresses both from its own weight and from the movements of the wearer; and if the cloth is disposed at 45° to this vertical stress one can exploit the resulting large lateral contraction so as to get a clinging effect. The result was no doubt cheaper and more comfortable than the Edwardian solutions to the problem and, in selected instances, probably more devastating (Plates 17 and 18).

An analogous problem arises with the design of large rockets. Some rockets are driven by combinations of liquid fuels such as kerosene and liquid oxygen, but these systems involve elaborate plumbing which is liable to go wrong. Thus it may be better to use a 'solid' fuel such as that known as 'plastic propellant'. This stuff burns vigorously but relatively slowly, producing a great volume of hot gas which escapes through the rocket nozzle with a most impressive noise, driving the thing along as it does so. Both the propellant and the gas which it produces are contained within a strong cylindrical case or pressure vessel, whose walls must not be unduly exposed to flames or to high temperatures. For this reason the rather massive propellant charge is shaped in the form of a thick tube which fits tightly into the rocket casing. When the rocket is fired, combustion takes place at the inner surface of the plastic propellant, so that the tubular charge burns from the inside outwards. In this way the material of the case is protected from the flames up to the last possible moment by the presence of the remaining unburnt fuel.

Plastic propellant looks and feels rather like plasticine, and, like plasticine, it is apt to break in a brittle way, especially when it is cold. When a rocket is firing, the case naturally tends to expand under the gas pressure, rather as an artery expands under blood-pressure; if it does so, then the propellant has to expand with it. If the interior of the charge is still cold, it is likely to crack when the circumferential strain in the case reaches about 1·0 per cent. If this happens, then the flames will penetrate down the crack and destroy the case. This naturally results in a sensational explosion as another Polaris bites the dust.

Round about 1950, it occurred to some of us that it would be advantageous to make the rocket case, not from a metal tube, but in the form of a cylindrical vessel, wound from a double helix of strong glass fibres, bonded together with a resin adhesive. If the fibre angles are calculated correctly, it is possible so to arrange things that the change of diameter of the tube under pressure is small. It is true that, in such a situation, the tube will elongate more than it otherwise would, like Mlle Vionnet's waists, but, for various reasons, a longitudinal extension is less damaging to the propellant. As I seem to remember, this idea about rockets stemmed from the bias-cut nighties which were around at the time.

The strain requirements for rockets are generally just the opposite of what is needed in blood-vessels. As we saw in Chapter 8, one wants an artery to maintain a constant length while exposed to fluctuations in blood-pressure (but changes in artery diameter are not important). Either condition can be met by making suitably designed tubes from helically disposed fibres. Problems of this kind keep cropping up in biology, and it was most interesting to find that Professor Steve Wainwright of Duke University, who is concerned with worms, has derived, quite independently, just the same mathematics as we had worked out twenty years or so before for use in rocketry.* On inquiry, I find that in this case too the inspiration arose, via Professor Biggs, from the bias cut.

The invention of the bias cut brought fame to Mlle Vionnet in the world of haute couture. She lived to a great age and died, not long ago, at ninety-eight, quite unaware of her very significant contributions to space travel, to military technology and to the biomechanics of worms.

Shear stress is only tension and compression acting at ±45° – and vice versa

A very little further thought about plate webs in beams and lattice webs in trusses and about bias-cut nighties makes it obvious that a shear stress is merely tension or compression (or both) acting at 45°, and that, furthermore, there is a shear stress acting at 45° to every tension and compression stress.

In fact solids, especially metals, very frequently break in tension by reason of the shear stress at 45°. It is this which leads to the 'necking' of metal rods and plates in tension and to the mechanics of ductility in metals (Figure 9 and Chapter 5).

As we shall see in the next chapter, very much the same thing can also occur in compression. That is to say, many solids break in compression by sliding away from the load in shear.

Creasing – or the Wagner tension field

A thick plate or a solid piece of metal is able to resist compression, and so, when such things are subjected to shearing loads, there

*The cuticles of many worms and other soft animals are strengthened by systems of helically disposed collagen fibres (Chapter 8). The worm has much the same problems as the dressmaker, though it is often more successful in solving them. It is difficult to put a crease into a worm.

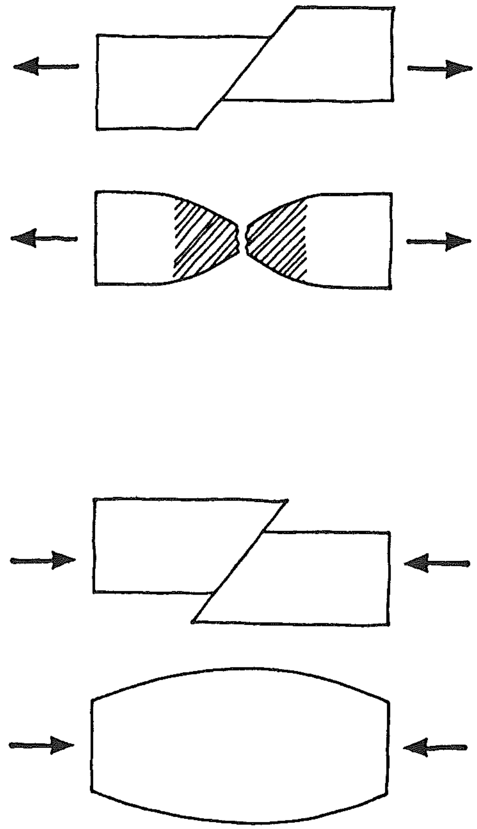


Figure 9. In ductile materials both tension and compression failure tend to occur by shear.

will exist, at ±45°, both tension and compressive stresses. Thin panels and membranes and films and fabrics are scarcely able to resist compression forces in their own plane, and so, when they are sheared, they are apt to crease. This creasing in shear is quite common in thin metal panels, such as occur in aircraft, and it is quite usual to see a creased or quilted effect on the surfaces of wings and fuselages due to this cause (Plate 19). This is called by engineers a 'Wagner tension field'.

The same effect is even more common in clothes and loose covers and tablecloths and badly cut sails. I suppose dressmakers do not very often talk about Wagner tension fields, but they do sometimes refer to that slightly mysterious quality which is known

in the textile trade as 'drape'. The drape of a fabric depends mainly upon its shear modulus, and although, very probably, few couturiers could quote any figures – in SI or any other units – for the shear modulus, *G*, of their silks and cottons, on the whole, the lower the shear modulus of a 'material', the less its tendency to unwanted creasing. The reason why we cannot dress ourselves in paper or Cellophane without appearing ridiculous is mainly that these substances have too high a shear stiffness, so that they will not drape properly. Contrariwise, knitted and crêped fabrics have both a low Young's modulus and a low shear modulus, so that it is easy to get a close and flexible fit – as girls have discovered with knitted sweaters. In the same way the skin of young people has a low initial Young's modulus and a low shear modulus and therefore conforms easily to the shape of the body.* In later life the skin becomes stiffer in shear, with obvious results. Recently Professor R. M. Kenedi of the University of Strathclyde has made an extensive study of elastic conformity in human skin. So, for the first time, the wrinkles of age are likely to be put on to a numerical or quantitative basis.

Torsion or twisting

The aeroplane was developed from an impossible object into a serious military weapon in something like ten years. This was achieved almost without benefit of science. The aircraft pioneers were often gifted amateurs and great sportsmen, but very few of them had much theoretical knowledge. Like modern car enthusiasts, they were generally more interested in their noisy and unreliable engines than they were in the supporting structure, about which they knew little and often cared less. Naturally, if you hot up the engine sufficiently, you can get almost any aeroplane into the air. Whether it stays there depends upon problems of control and stability and structural strength which are conceptually difficult.

*Note that, for an initially flat membrane to conform easily to a surface with pronounced two-dimensional curvature, it is necessary to have *both* a low Young's modulus *and* a low shear modulus. This is essentially the problem of map-projection which was encountered by Mercator about 1560.

In the early days too many brave men, like C. S. Rolls and S. F. Cody, paid with their lives for this attitude of mind. The theoretical basis of aerodynamics had been worked out by F. W. Lanchester in the 1890s, but not many practical men had the least idea what he was talking about.* A good many of the accidents to the pioneers were caused by stalls and spins, but structural failures were nearly as common. Since the early pilots seldom used parachutes, these accidents were generally fatal.

The requirement for a really reliable lightweight engineering structure was, of course, more or less a new one. In the first place, the wings of an aircraft are subject to bending forces, very much like a bridge. Since this is obvious, and since there was a good deal of precedent to go on in the matter of bridge construction, bending loads could generally be dealt with more or less safely. What was not so often realized was that the wings of an aeroplane are, in addition, subject to large torsional or twisting forces. If no proper provision is made to resist these torsions, the wings will be twisted off.

With the expansion of military flying after war broke out in 1914, the accident rate became a serious matter. In this country, luckily, such questions were dealt with by that small group of brilliant young men at Farnborough who afterwards became famous as Lord Cherwell, Sir Geoffrey Taylor, Sir Henry Tizard and 'Jehovah' Green. Thanks to their efforts the traditional biplane became, by 1918, one of the safest of all structures and came to be regarded as almost unbreakable. The Germans were less fortunate. Their aircraft technical authorities at that period had the reputation of being rather hidebound. At any rate they had a long run of structural accidents – many of them due to a failure to understand the problem of torsion in aircraft wings.

By the early part of 1917 the Allies had achieved a degree of

*Nor had many of the academic engineers. Even as late as 1936, the basic Lanchester-Prandtl (or vortex) theory of fluid dynamics was neither taught nor permitted to be used in the Department of Naval Architecture in the University of Glasgow. To those of a younger generation who may not be disposed to believe this story, I would point out that (a) I was myself a student in the department at the time, and (b) much the same sort of thing happens with 'modern' theories of fracture mechanics (Chapter 5) in present-day engineering departments.

air superiority on the western front, partly as a result of the technical quality of their fighters. However, in the meantime, the very able designer Antony Fokker was developing an advanced monoplane fighter – the Fokker D8 – with a performance better than anything available or in immediate prospect on the Allied side. Because of the critical tactical situation, production of the D8 was accelerated and it was issued to several of the crack German fighter squadrons without undergoing any adequate programme of test flying.

As soon as the D8 was flown under combat conditions it was found that, when the aircraft was pulled out of a dive in a dogfight, the wings came off. Since many lives were lost – including those of some of the best and most experienced German fighter pilots – this was a matter of very grave concern to the Germans at the time, and it is still instructive to study the cause of the trouble.

In those days most aircraft were biplanes, because this form of construction was lighter and also more reliable. However, for a given engine power, a monoplane will generally be faster than a biplane, because it does not have to experience the extra air resistance resulting from the aerodynamic interference which occurs between two adjacent sets of wings. There was thus a strong inducement to build monoplane fighters. However, although the reasons for the many failures were not understood, monoplanes had been known to be structurally unreliable ever since the wings of Samuel Langley's historic aeroplane had collapsed over the Potomac river in America in 1903.

The wings of the Fokker D8, like those of most monoplanes at the time, were fabric-covered. The fabric was there solely to provide the desired aerodynamic shape. It was merely stretched over an internal structural framework and itself carried none of the main loads. The main bending loads were taken by two parallel wooden spars or cantilever beams which projected sideways from the fuselage. The two spars were connected every few inches by a series of light shaped wooden ribs, to which the doped fabric was attached (Figure 10).

As soon as the accidents to the D8 became known the German Air Force authorities very naturally ordered structural tests to be made. After the custom of the time, a complete aircraft was

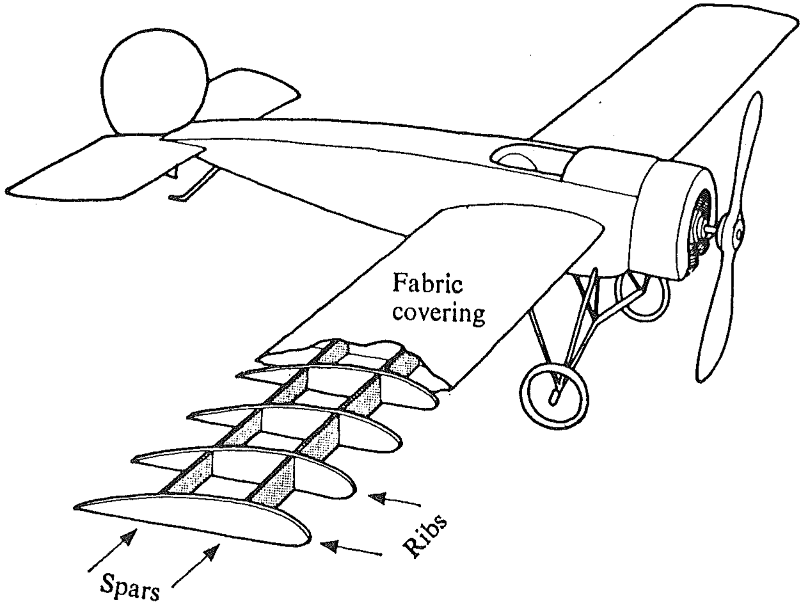


Figure 10. Fabric-covered monoplane wing.

mounted upside down in a test-frame and the wings were loaded with piles of shot-bags, disposed so as to simulate the aerodynamic loads which occur in flight. When tested in this way the wings showed no sign of weakness, and they were broken only by a load which was equivalent to six times the total loaded weight of the aircraft. Although nowadays fighter aircraft are required to withstand a load equivalent to twelve times their own weight, in 1917 a 'factor' of six was considered entirely adequate and almost certainly represented a bigger load than would have occurred under the worst combat conditions at the time. In other words, the aircraft should have been perfectly safe.

However, in the D8, when structural collapse did eventually happen on the test-rig, the failure could be seen to begin in the after of the two spars. To make quite certain, therefore, the authorities ordered the rear spars of all Fokker D8s to be replaced by thicker and stronger ones. Unfortunately, after this had been done, the accidents became more, not less, frequent, and so the German Air Ministry had to face the fact that by 'strengthening' the wing by adding more structural material they had actually made it weaker.

By this time it was becoming clear to Antony Fokker that he was not going to get much effective help from the official mind. He therefore loaded up another D8 under his own supervision in his own factory. This time he took care to measure the deflections which occurred in the wing when it was loaded. What he found was not only that when the wing was loaded it deflected in bending (that is to say, the wing-tips would rise with respect to the fuselage when the plane was pulled out of a dive), but also that the wings twisted although no obvious twisting loads had been applied to them. What was particularly important was that the direction of this twisting was such that the aerodynamic incidence, or angle of attack of the wing, was significantly increased.

Pondering over these results that night, it suddenly occurred to Fokker that here lay the solution to the D8 accidents and to a great many other monoplane troubles as well. When the pilot pulled the control-stick back the nose of the plane rose and so did the load on the wings. *But* at the same time the wings twisted, so that air loads on the wings rose disproportionately; so the wings twisted more; so the loads rose still more; and so on, until the pilot no longer had any control over the situation and the wings were twisted off. Fokker had discovered something which is called a 'divergent condition' – which can also be a very lethal one.

What was actually happening in terms of elasticity?

Centres of flexure and centres of pressure

Consider a pair of similar, parallel, cantilever beams or wing-spars, joined together at intervals by horizontal fore and aft ribs bridging the gap between them (Figure 10). Suppose now a single upward force to be applied at some point on one of the outer ribs. Unless this force is applied at a point which is just half-way between the two cantilever spars (Figure 11), the load will not be equally shared between the spars and the upward force will be greater on one spar than on the other. If this happens then the more heavily loaded spar must deflect upwards further than its

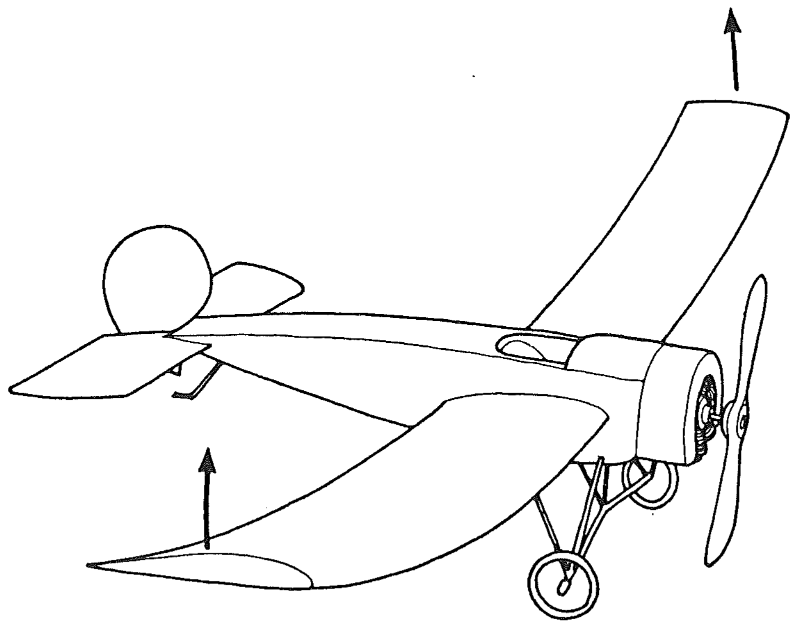
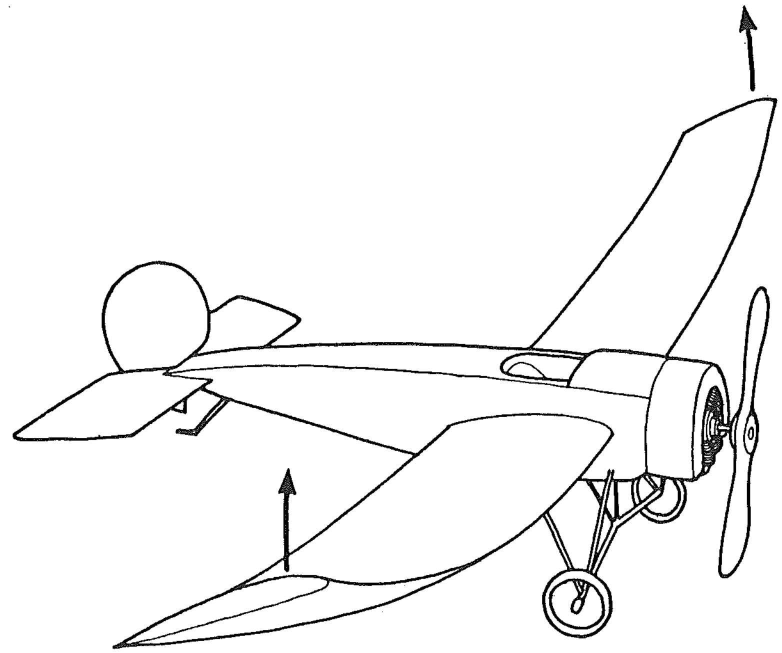


Figure 11. Coupled bending and torsion. *Only* if the vertical lift forces act effectively at a point called the 'flexural centre' (in this case half-way between the two spars) will the wings bend upwards without twisting.

partner (Figure 12). In such a case the ribs joining the spars will cease to be horizontal and the wing as a whole must twist. The point at which a load must be applied so as to cause no twisting in a beam-like structure is called the 'centre of flexure' or the 'flexural centre'.

Naturally, if there are more than two spars, or if the spars are of differing stiffness, then the flexural centre will not be at the mid-point but at some other position along the fore and aft or chord line. *However, there is always a centre of flexure associated with every sort of beam or beam-like structure.* A vertical load applied at this point will not cause the beam or wing to twist; a load applied at any other fore and aft position will cause a greater or less amount of twisting or torsional deflection *as well* as the usual bending deflection.

So far we have argued the case in terms of a single point load applied to a beam or a wing. Naturally, the aerodynamic lifting



Fgure 12. If the lift forces act at a point *away* from the flexural centre (e.g. near the leading edge of a wing), then the wing (or any other beam) will twist as it bends. If this causes an increase of aerodynamic incidence the result may be fatal, as it was in the Fokker D8.

forces which, when an aircraft is in flight, press upwards on a wing and so keep the machine in the air are diffused over the whole of the wing surface. However, for the purposes of discussion and calculation all these forces can be considered as acting together at a single point on the wing surface which is known as the 'centre of pressure' or C.P.

It might perhaps be supposed by the uninitiated that the C.P. of the lift forces acting on a wing in flight lay at the middle of the wing, half-way between the leading and trailing edges, that is to say, at mid-chord. Actually it is a well-known fact of aerodynamic life that this is just what does not happen. The centre of pressure of the lift forces on a wing is really not far behind the leading edge, usually near to what is called the 'quarter-chord' position: that is to say, 25 per cent of the chord behind the leading edge.*

*This is why a dead leaf or a sheet of cardboard falls in the way it does.

It follows that, unless the structure of the wing is designed so that the flexural centre is close to the quarter-chord position, the wing must twist. The angle through which the wing will twist will naturally depend upon how stiff the wing is in torsion, but, on the whole, all wing-twisting is a bad and dangerous thing in an aeroplane and it is the designer's aim to reduce it as much as possible. This is why the quill of a bird's wing feather is usually located around the quarter-chord position (Figure 13).

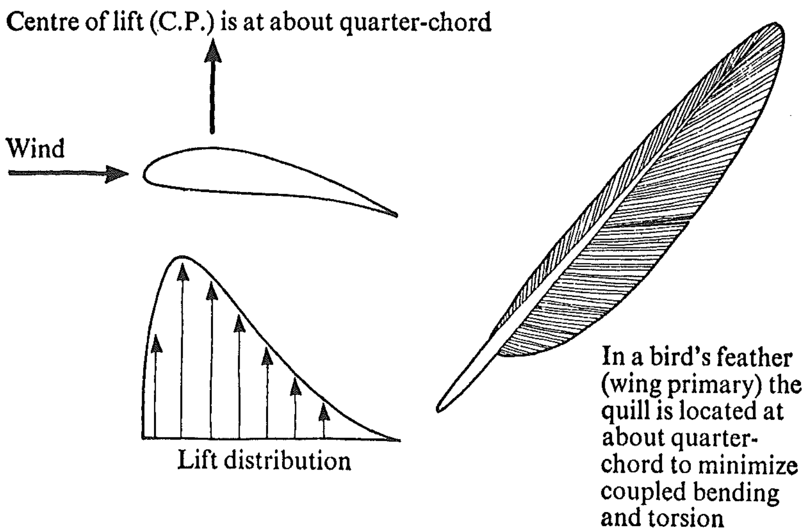


Figure 13. Lift distribution across an aerofoil.

In a simple fabric-covered monoplane wing both the position of the centre of flexure and also the torsional stiffness depend almost entirely upon the relative bending stiffnesses of the main spars. In the Fokker D8 the centre of flexure was a long way behind the centre of pressure and much too near mid-chord. The wing had not enough stiffness to resist the resulting torsional forces and so it was twisted off. Modifications which strengthened and stiffened the *rear* spar had the effect of moving the flexural centre still further backwards and so made the situation even worse. When these facts dawned on Antony Fokker he took the by now obvious step of *reducing* the thickness and stiffness of the rear spar, thus moving the centre of flexure further forward and closer

to the C.P. When this was done the D8 became, comparatively speaking, a safe machine and a menace to the Royal Flying Corps and the French Air Force.

Because of the laws of aerodynamics the C.P. of the lift forces acting on an aeroplane wing must always be near to the quarter-chord position. To reduce the torsional or twisting stresses in the wing it is therefore necessary to design the structure in such a way that the centre of flexure is well forward in the wing and lies close to the C.P. However, the ailerons (which control the aircraft in roll, that is to say, when banking) apply large up or down forces to the wing tips, and these forces act at points not far from the trailing edge and thus a long way to the rear of the centre of flexure. Thus the ailerons inevitably exert large twisting loads on the wings every time the pilot banks the aircraft. It will be seen from Figure 14 that the direction of this twist is such as to change

Figure 14. An aileron applies large vertical loads near the trailing edge of a wing and well *aft* of the wing's flexural centre. It therefore tends to twist the wing in such a way as to provide aerodynamic forces which are the *opposite* of those desired by the pilot.

the aerodynamic lift on the wing, as a whole, in the *opposite sense* to the action of the aileron and thus to reduce its effect. If the wing is not sufficiently stiff in torsion the effect of the aileron may actually be reversed, so that the pilot, wanting to roll or bank the aircraft to the *right*, and applying his controls in that sense, may find that the aircraft actually rolls to the *left*. This effect, which is not only disconcerting but also very dangerous, is called 'aileron reversal' and is not unknown. It is a serious problem in the design of modern fast aircraft. The cure or preventive is to ensure ample torsional stiffness in the wing structure.

In the early fabric-covered monoplanes, such as the D8, the torsional stiffness of the wings was almost entirely due to what is called the 'differential bending' of the two main spars. Not very much can be done about this and the amount of torsional stiffness which can be obtained from such a system – even with the help of a certain amount of wire rigging – is quite limited. For this reason such aircraft were always more or less dangerous – so much so that the authorities in nearly every country frowned on monoplane construction, and in some cases it was actually forbidden.

The preference for biplanes was, therefore, not due to some kind of reactionary stupidity on the part of air ministries but rather to the fact that the biplane provides what is inherently a stiffer and stronger form of construction – especially in torsion. In practice, biplanes were both lighter and safer than monoplanes for many years, and in the early days the difference in speed was not very great.

What the strutted and braced biplane construction does is to provide, in effect, a sort of cage or 'torsion box' which is very strong and stiff, not only in bending but also in torsion. From Figure 15 it will be seen that the four main spars (two in each wing) run along the corners of the box, while the spaces between them form a braced truss or lattice girder. One does not, of course, see the diagonal bracing on the top and bottom surfaces, because it is hidden by the fabric of the wings. However, this horizontal bracing is there all right, and its function is to take the shears which arise from the torsions in the wing structure. The manner in which such a box can resist torsion is shown diagrammatically in the figure. It will be seen that each side of the box is being sheared individually, very much like the lattice web of a trussed beam which is in bending. Notice that all four sides of the box are being sheared together and that they are mutually dependent. If one of the four sides were cut or removed there would be no resistance at all to torsion.

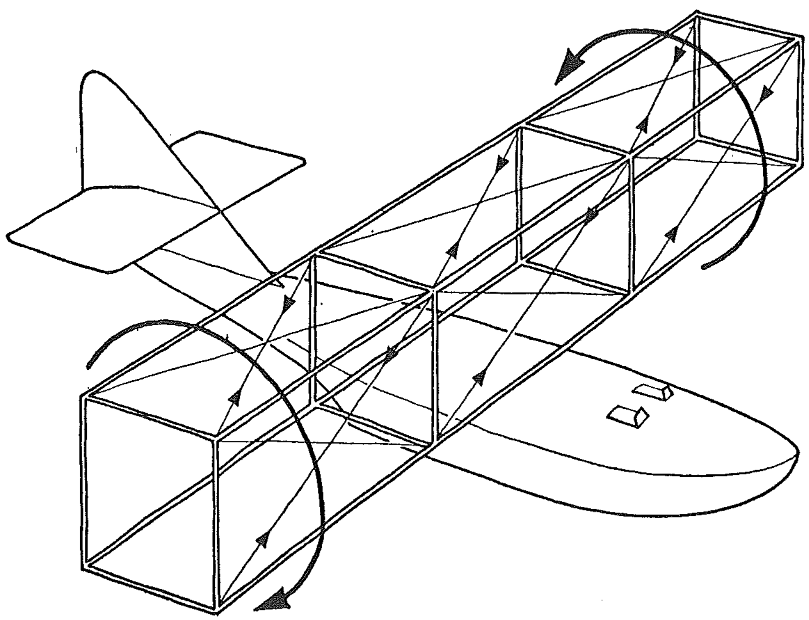


Figure 15. Diagram of the main structure of a pair of wire-braced biplane wings subject to torsional forces, e.g. from the ailerons. The whole affair forms what is called a 'torsion box'.

In a biplane these shear panels are necessarily made from struts and wires. However, if the structure did not have to fly but merely had to resist torsional forces on the ground, then the lattice of wires and struts could be replaced by continuous panels of metal or sheets of plywood. From a purely structural point of view the effect would be the same, just as it would be in the web of a beam truss. Torsion can therefore be resisted by any kind of box or tube whose sides may be continuous or alternatively of openwork lattice construction. In either case the walls or sides of the tube are subject to shearing stresses. In terms of weight and strength and stiffness this is a very much more effective way of resisting torsion than depending on the differential bending of two beams.

Formulae for the strength and stiffness in torsion of various kinds of rods and tubes are given in Appendix 3. Among other things it will be noticed that the strength and stiffness in twisting of a tube or torsion box depends upon the *square* of the area of its cross-section. Thus a torsion box of large cross-section, such as an old-fashioned biplane, will require little material and will be light in weight. When we build a modern monoplane, what we do is to turn the wing itself into a torsion tube with a continuous covering of metal sheet or plywood. However, even though we, perforce, use a much thicker wing than was the practice with biplanes, yet the cross-sectional area of the torsion tube, as a whole, is still much less than that of the biplane. So to get adequate torsional strength and stiffness we are forced to use comparatively thick and heavy skin. Thus a comparatively high proportion of the weight of the structure of modern aircraft has to be devoted to resisting torsion.

Although a lack of torsional stiffness is not quite as dangerous in cars as in aircraft, the character of a car's suspension and road-holding does largely depend upon it. The pre-war vintage cars were sometimes magnificent objects, but, like vintage aircraft, they suffered from having had more attention paid to the engine and the transmission than to the structure of the frame or chassis. These chassis, in fact, usually relied for any torsional stiffness which they might have had upon the differential bending of rather flexible beams – much like the old Fokker D8. It was the lack of stiffness in the chassis which gave these cars their highly uncertain road-holding characteristics and which made them so tiring to drive.

In an attempt to keep the wheels more or less in contact with the ground the springs and shock-absorbers of the vintage sports cars were stiffened up until they were virtually solid. As a result, of course, the ride became almost unbearably rough and jerky. Like the noisy exhaust, this kind of thing was no doubt impressive to the girl passenger, but it did not really do very much to keep the car on the road. The solution adopted by most modern car designers is to scrap the rather flimsy chassis and to take the torsion and bending loads through the pressed-steel 'saloon' body shell. This forms, with its roof, a big torsion box not wholly unlike the old biplanes. With so much stiffness at his disposal the designer can concentrate on providing a scientifically designed suspension which is both safe and comfortable.

As we have said, the strength and stiffness of a structure in torsion vary as the square of the area of its cross-section. This is more or less all right with bulky things like aircraft wings and ships' hulls and saloon cars; but when we come to shafts in engines and machinery the diameter – and therefore the area of the cross-section – is usually very limited, and so, as a rule, such members need to be made from solid steel. Even then, although they are often very massive, they are not always sufficiently strong. This is one of the reasons why engines and machinery are usually so heavy. As most experienced designers will tell you, any major requirement for torsional strength and stiffness in a structure is apt to be a curse and a blight. It puts up the weight and the expense and altogether provides a quite disproportionate amount of trouble and anxiety to the engineer.

Nature does not seem to mind taking a lot of time and trouble, and she has no sense at all of the value of money; but she is intensely sensitive to 'metabolic cost' – that is to say, to the price of a structure in terms of food and energy – and she is also generally pretty weight-conscious. It is not surprising, therefore, that she seems to avoid torsion like poison. In fact she nearly always manages to dodge out of any serious requirement for the provision of torsional strength or stiffness. As long as they are not subjected to 'unnatural' loads, most animals can afford to be weak in torsion. None of us likes having our arm twisted, and in normal life the torsional loads on our legs are small. However, when we attach long levers called skis to our feet and then proceed to ski rather badly, it is only too easy to apply large twisting forces to our legs. Because this is the commonest cause of broken legs in ski-ing, it has led to the development of the modern safety binding, which releases automatically in torsion.

Not only our legs, but virtually all bones, are surprisingly weak in torsion. Should you wish to kill a chicken – or any other bird – much the easiest way is to wring its neck. This is well known; what is less well known is how very weak are the vertebrae in torsion, as the beginner is apt to find out to his disgust and embarrassment when the head comes off in his hand. But then neck-wringing, like ski-ing, is an entirely artificial hazard and quite out of the ordinary course of nature. Unlike engineers, Nature has little interest in rotary motion and (like the Africans) she has never bothered to invent the wheel.