were employed in the straw industry, and in 1881 the number was only about 31,000. The plaits are sewed partly by hand and in a special sewing-machine, and the hats or bonnets are finished by stiffening with gelatin size, and blocking into shape with the aid of heat and powerful pressure, according to the dictates of fashion. The annual output of the straw-plait industry in England is estimated to amount in value to about £4,000,000.

In the United States straw-plait work is principally centred in the State of Massachusetts.

Many substances besides straw are worked into plaits and braids for bonnets. Among these may be noticed thin strips of willow and cane, and the fronds of numerous palms. "Brazilian" hats made from the fronds of the palmetto palms, *Sabal Palmetto* and *S. mexicana*, are now largely made at St Albans. The famous Panama hats, fine qualities of which at one time were worth £20 to £30 each, are made from the leaves of the screw pine, *Carludovica palmata*. They are now manufactured at Dresden, Strasburg, and Nancy, and can be purchased at 30s. or £2.

STREET, George Edmund (1824–1881), one of the ablest architects of the present century, was born at Woodford in Essex in 1824. He obtained his architectural education in the office of Mr Owen Carter at Winchester, and afterwards worked for five years as an "improver" with Sir G. G. Scott in London. At an early age Street became deeply interested in the principles of Gothic architecture, and devoted an unsparing amount of time and labour to studying and sketching the finest examples of mediæval buildings in England and on the Continent. He was a draughtsman of a very high order; his sketches are masterpieces of spirit and brilliant touch. In 1855 he published a very careful and well illustrated work on *The Brick and Marble Architecture of Northern Italy*, and in 1865 a book on *The Gothic Architecture of Spain*, with very beautiful drawings by his own hand. Street's personal taste led him in most cases to select for his design the 13th-century Gothic of England or France, his knowledge of which was very great, especially in the skilful use of rich mouldings. By far the majority of the buildings erected by him were for ecclesiastical uses, the chief being the convent of East Grinstead, the theological college at Cuddesden, and a very large number of churches, such as St Philip and St James's at Oxford, St John's at Torquay, All Saints at Clifton, St Saviour's at Eastbourne, St Margaret's at Liverpool, and St Mary Magdalene, Paddington. His largest works were the nave of Bristol cathedral, the choir of the cathedral of Christ Church in Dublin, and, above all, the new Courts of Justice in London, second only in architectural importance (during this century) to the Houses of Parliament. After a prolonged competition Street was appointed architect to the Courts of Justice in 1868; but the building was not complete at the time of his death in December 1881. A great deal of somewhat unfair criticism has been lavished on this building; but it should be remembered that Street was much hampered both by want of a sufficiently large site and by petty economies in money insisted on by the commissioner of works. Though perhaps deficient in unity of composition, this great building possesses much grace in its separate parts, and has great refinement of detail throughout. Street was elected an associate of the Royal Academy in 1866 and R.A. in 1871; at the time of his death he was professor of history to the Royal Academy, and had just finished a very interesting course of lectures on the development of mediæval architecture. He was also a member of the Royal Academy of Vienna, and a knight of the Legion of Honour. His somewhat sudden death, on December 18, 1881, was hastened by over-work and professional worries connected with the erection of the law courts. He was buried in the nave of Westminster Abbey, where his grave is marked by a handsome sepulchral brass designed by Mr Bodley.

STREETS. See Roads.

STRENGTH OF MATERIALS

1. THE name "strength of materials" is given to that part of the theory of engineering which deals with the nature and effects of stresses in the parts of engineering structures. Its principal object is to determine the proper size and form of pieces which have to bear given loads, or, conversely, to determine the loads which can be safely applied to pieces whose dimensions and arrangement are already given. It also treats of the relation between the applied loads and the changes of form which they cause. The subject comprises experimental investigation of the properties of materials as to strength and elasticity, and mathematical discussion of the stresses in ties, struts, beams, shafts, and other elements of structures and machines.

2. Stress is the mutual action at the surface of contact between two bodies, or two imaginary parts of a body, whereby each of the two exerts a force upon the other. Thus, when a stone lies on the ground there is at the surface of contact a stress, one aspect of which is the force directed downwards with which the stone pushes the ground, and the other aspect is the equal force directed upwards with which the ground pushes the stone. A body is said to be in a state of stress when there is a stress between the two parts which lie on opposite sides of an imaginary surface of section. A pillar or block supporting a weight is in a state of stress because at any cross section the part above the section pushes down against the part below, and the part below pushes up against the part above. A stretched rope is in a state of stress, because at any cross section the part on each side is pulling the part on the other side with a force in the direction of the rope's length. A plate of metal that is being cut in a shearing machine is in a state of stress, because at the plane which is about to become the plane of actual section the portion of metal on each side is tending to drag the portion on the other side with a force in that plane.

Normal and tangential stress.

3. In a solid body which is in a state of stress the direction of stress at an imaginary surface of division may be normal, oblique, or tangential to the surface. When oblique it is often conveniently treated as consisting of a normal and a tangential component. Normal stress may be either push (compressive stress) or pull (tensile stress). Stress which is tangential to the surface is called shearing stress. Oblique stress may be regarded as so much push or pull along with so much shearing stress. The amount of stress per unit of surface is called the intensity of stress. Stress is said to be uniformly distributed over a surface when each fraction of the area of surface bears a corresponding fraction of the whole stress. If a stress P is uniformly distributed over a plane surface of area S, the intensity is P/S. If the stress is not uniformly distributed, the intensity at any point is $\delta P/\delta S$, where δP is the amount of stress on an indefinitely small area δS at the point considered. For practical purposes intensity of stress is usually expressed in tons weight per square inch, pounds weight per square inch, or kilogrammes weight per square millimetre or per square centimetre.[1]

4. The simplest possible state of stress is that of a short pillar or block compressed by opposite forces applied at its ends, or that of a stretched rope or other tie. In these cases the stress is wholly in one direction, that of the length. These states may be distinguished as simple longitudinal push and simple longitudinal pull. In them there is no stress on planes parallel to the direction of the applied forces.

A more complex state of stress occurs if the block is compressed or extended by forces applied to a pair of opposite sides, as well as by forces applied to its ends,—that is to say, if two simple longitudinal stresses in different directions act together. A still more complex state occurs if a third stress be applied to the remaining pair of sides. It may be shown that any state of stress which can possibly exist at any point of a body may be produced by the joint action of three simple pull or push stresses in three suitably chosen directions at right angles to each other.[2] These three are called principal stresses, and their directions are called the axes of principal stress. These axes have the important property that the intensity of stress along one of them is greater, and along another it is less, than in any other direction. These are called respectively the axes of greatest and least principal stress.

5. Returning now to the case of a single simple longitudinal stress, let AB (fig. 1) be a portion of a tie or a strut which is being pulled or pushed in the direction of the axis AB with a total stress P. On any plane CD taken at right angles to the axis we have a normal pull or push of intensity $p=P/S$, S being the area of the normal cross-section. On a plane EF whose normal is inclined to the axis at an angle θ we have a stress still in the direction of the axis, and therefore oblique to the plane EF, of intensity P/S', where S' is the area of the surface EF, or $S/\cos\theta$. The whole stress P on EF may be resolved into two components, one normal to EF, and the other a shearing stress tangential to EF. The normal component (P_n, fig. 2) is $P\cos\theta$; the tangential component (P_t) is $P\sin\theta$. Hence the intensity of normal pull or push on EF, or p_n, is $p\cos^2\theta$, and the intensity of shearing stress EF, or p_t, is $p\sin\theta\cos\theta$. This expression makes p_t a maximum when $\theta=45°$: planes inclined at 45° to the axis are called planes of maximum shearing stress; the intensity of shearing stress on them is $\frac{1}{2}p$.

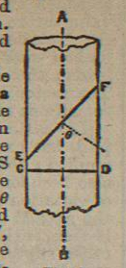

Fig. 1.

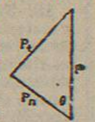

Fig. 2.

6. Shearing stress in one direction is necessarily accompanied by an equal intensity of shearing stress in another direction at right angles to the first. To prove this it is sufficient to consider the equilibrium of an indefinitely small cube (fig. 3), with one pair of sides parallel to the direction of the shearing stress P_t. This stress, acting on two opposite sides, produces a couple which tends to rotate the cube. No arrangement of normal stresses on any of the three pairs of sides of the cube can balance this couple; that can be done only by a shearing stress Q_t whose direction is at right angles to the first stress P_t and to the surface on which P_t acts, and whose intensity is the same as that of P_t. The shearing stresses P_t and Q_t may exist alone, or as components of oblique stress.

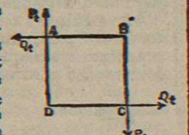

Fig. 3.

7. If they exist alone, the material is said to be in a state of simple shearing stress. This state of stress may be otherwise described by reference to the stresses on diagonal planes of the cube ABCD. Thus P_t and Q_t produce a normal stress R on a diagonal plane, and the equilibrium of the triangular prism (fig. 4) requires that $R=P_t\sqrt{2}$. But R acts on a surface which is greater than each of the sides in the ratio of $\sqrt{2}:1$. The intensity of normal stress on the diagonal plane AC is therefore the same as the intensity of shearing stress on AB or BC. The same considerations apply to the other diagonal plane BD at right angles to AC, with this difference, that the stress on it is normal pull instead of push. Hence we may regard a state of simple shearing stress as compounded of two simple longitudinal stresses, one of push and one of pull, at right angles to each other, of equal intensity, and inclined at 45° to the direction of the shearing stress.

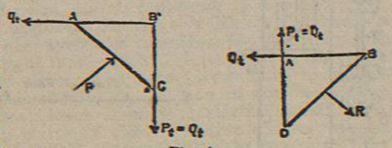

Fig. 4.

8. Strain is the change of shape produced by stress. If the stress is a simple longitudinal pull, the strain consists of lengthening in the direction of the pull, accompanied by contraction in both directions at right angles to the pull. If the stress is a simple push, the strain consists of shortening in the direction of the push and expansion in both directions at right angles to that; the stress and the strain are then exactly the reverse of what they are in the case of simple pull. If the stress is one of simple shearing, the strain consists of a distortion such as would be produced by the sliding of layers in the direction of the shearing stresses.

A material is elastic with regard to any applied stress if the strain disappears when the stress is removed. Strain which persists after the stress that produced it is removed is called permanent set. For brevity, it is convenient to speak of strain which disappears when the stress is removed as elastic strain.

9. Actual materials are generally very perfectly elastic with regard to small stresses, and very imperfectly elastic with regard to great stresses. If the applied stress is less than a certain limit, the strain is in general small in amount, and disappears wholly or almost wholly when the stress is removed. If the applied stress exceeds this limit, the strain is, in general, much greater than before, and the principal part of it is found, when the stress is removed, to consist of permanent set. The limits of stress within which strain is wholly or almost wholly elastic are called limits of elasticity.

For any particular mode of stress the limit of elasticity is much more sharply defined in some materials than in others. When well defined it may readily be recognized in the testing of a sample from the fact that after the stress exceeds the limit of elasticity the strain begins to increase in a much more rapid ratio to the stress than before. This characteristic goes along with the one already mentioned, that up to the limit the strain is wholly or almost wholly elastic.

10. Within the limits of elasticity the strain produced by a stress of any one kind is proportional to the stress producing it. This is Hooke's law, enunciated by him in 1676.

In applying Hooke's law to the case of simple longitudinal stress,—such as the case of a bar stretched by simple longitudinal pull,—we may measure the state of strain by the change of length per unit of original length which the bar undergoes when stressed. Let the original length be l, and let the whole change of length be δl when a stress is applied whose intensity p is within the elastic limit. Then the strain is measured by $\delta l/l$, and this by Hooke's law is proportional to p. This may be written

$$\delta l : l :: p : E,$$

where E is a constant for the particular material considered. The same value of E applies to push and to pull, these modes of stress being essentially continuous, and differing only in sign.

11. This constant E is called the modulus of longitudinal extensibility, or Young's modulus. Its value, which is expressed in the same units as are used to express intensity of stress, may be measured directly by exposing a long sample of the material to longitudinal pull and noting the extension, or indirectly by measuring the flexure of a loaded beam of the material, or by experiments on the frequency of vibrations. It is frequently spoken of by engineers simply as the modulus of elasticity, but this name is too general, as there are other moduluses applicable to other modes of stress. Since $E=pl/\delta l$, the modulus may be defined as the ratio of the intensity of stress p to the longitudinal strain $\delta l/l$.

12. In the case of simple shearing stress, the strain may be measured by the angle by which each of the four originally right angles in the square prism of fig. 3 is altered by the distortion of the prism. Let this angle be ϕ in radians; then by Hooke's law $p/\phi=C$, where p is the intensity of shearing stress and C is a constant which measures the rigidity of the material. C is called the modulus of rigidity, and is usually determined by experiments on torsion.

13. When three simple stresses of equal intensity p and of the same sign (all pulls or all pushes) are applied in three directions, the material (provided it be isotropic, that is to say, provided its properties are the same in all directions) suffers change of volume only, without distortion of form. If the volume is V and the change of volume δV, the ratio of the stress p to the strain $\delta V/V$ is called the modulus of cubic compressibility, and will be denoted by K. The state of stress here considered is the only one possible in a fluid at rest. The intensity of stress is equal in all directions.

14. Of these three moduluses the one of most importance in engineering applications is Young's modulus E. When a simple longitudinal pull or push of intensity p is applied to a piece, the longitudinal strain of extension or compression is p/E. This is accompanied by a lateral contraction or expansion, in each transverse direction, whose amount may be written $p/\sigma E$, where σ is the ratio of longitudinal to lateral strain. It is shown in the article Elasticity, § 47, that $E=\dfrac{9CK}{3K+C}$ and $\sigma=\dfrac{2(3K+C)}{3K-2C}$.

15. Beyond the limits of elasticity the relation of strain to stress becomes very indefinite. Materials then exhibit, to a greater or less degree, the property of plasticity. The strain is much affected by the length of time during which the stress has been in operation, and reaches its maximum, for any assigned stress, only after a long (probably an indefinitely long) time. Finally, when the stress is sufficiently increased, the ratio of the increment of strain to the increment of stress becomes indefinitely great if time is given for the stress to take effect. In other words, the substance then assumes what may be called a completely plastic state; it *flows* under the applied stress like a viscous liquid.

16. The *ultimate strength* of a material with regard to any stated mode of stress is the stress required to produce rupture. In reckoning ultimate strength, however, engineers take, not the actual intensity of stress at which rupture occurs, but the value which this intensity would have reached had rupture ensued without previous alteration of shape. Thus, if a bar whose original cross-section is 2 square inches breaks under a uniformly distributed pull of 60 tons, the ultimate tensile strength of the material is reckoned to be 30 tons per square inch, although the actual intensity of stress which produced rupture may have been much greater than this, owing to the contraction of the section previous to fracture. The convenience of this usage will be obvious from an example. Suppose that a piece

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[1] One ton per sq. in. = 2240 lb per sq. in. = 1·511 kilos. per sq. mm.

[2] See Elasticity, vol. vii. p. 819.

of material of the same quality be used in a structure under conditions which cause it to bear a simple pull of 6 tons per square inch; we conclude at once that the actual load is one-fifth of that which would cause rupture, irrespective of the extent to which the material might contract in section if overstrained. The stresses which occur in engineering practice are, or ought to be, in all cases within the limits of elasticity, and within these limits the change of cross-section caused by longitudinal pull or push is so small that it may be neglected in reckoning the intensity of stress.

Ultimate tensile strength and ultimate shearing strength are well defined, since these modes of stress (simple pull and simple shearing stress) lead to distinct fracture if the stress is sufficiently increased. Under compression some materials yield so continuously that their ultimate strength to resist compression can scarcely be specified; others show so distinct a fracture by crushing (§ 43 below) that their compressive strength may be determined with some precision. In what follows, the three kinds of ultimate strength will be designated by the symbols f_t, f_s, and f_c, for tension, shearing, and crushing respectively.

Some of the materials used in engineering, notably timber and wrought-iron, are so far from being isotropic that their strength is widely different for stresses in different directions. In the case of wrought-iron the process of rolling develops a fibrous structure on account of the presence of streaks of slag which become interspersed with the metal in puddling; and the tensile strength of a rolled plate is found to be considerably greater in the direction of rolling than across the plate. Steel plates, being rolled from a nearly homogeneous ingot, have nearly the same strength in both directions.

17. In applying a knowledge of the ultimate strength of materials to determine the proper sizes of parts in an engineering structure, these parts are proportioned so that the greatest intensity of stress (which for brevity is called the working stress) will be only a certain fraction of the ultimate strength. The ratio $\frac{\text{ultimate strength}}{\text{working stress}}$ is called the factor of safety.[1] The choice of a factor of safety depends on many considerations, such as the probable accuracy of the theory on which the calculation of working stress has been based; the uniformity of the material dealt with, and the extent to which its strength may be expected to conform to the assumed value or to the values determined by experiments on samples; the deviations from the specified dimensions which may be caused by bad workmanship; the probable accuracy in the estimation of loads; the extent to which the materials will deteriorate in time. The factor is rarely less than 3, is very commonly 4 or 5, and is sometimes as much as 12, or even more.

The ultimate strength for any one mode of stress, such as simple pull, has been found to depend on the time rate at which stress is applied; this will be noticed more fully later (§§ 28–34). It has also been found to depend very greatly on the extent and frequency of variation in the applied stress. A stress considerably less than the normal ultimate strength will suffice to break a piece when it is frequently applied and removed; a much smaller stress will cause rupture if its sign is frequently reversed; and hence in a structure which has to bear what is called live load the permissible intensity of stress is less than in a structure which has to bear only load and also on its frequency of variation (§§ 45, 46 below).

18. From an engineering point of view, the structural merit of a material, especially when live loads and possible shocks have to be sustained, depends not only on the ultimate strength but also on the extent to which the material will bear deformation without rupture. This characteristic is shown in tests made to determine tensile strength by the amount of ultimate elongation, and also by the contraction of the cross-section which occurs through the flow of the metal before rupture. It is often tested in other ways, such as by bending and unbending bars in a circle of specified radius, or by examining the effect of repeated blows. Tests by impact are generally made by causing a weight to fall through a regulated distance on a piece of the material supported as a beam.

19. Ordinary tests of strength are made by submitting the piece to direct pull, direct compression, bending, or torsion. Testing machines are frequently arranged so that they may apply any of these four modes of stress; tests by direct tension are the most common, and next to them come tests by bending. When the samples to be tested for tensile strength are mere wires, the stress may be applied directly by weights; for pieces of larger section some mechanical multiplication of force becomes necessary. Owing to the plasticity of the materials to be tested, the applied loads must be able to follow considerable change of form in the test-piece: thus in testing the tensile strength of wrought-iron or steel provision must be made for taking up the large extension of length which occurs before fracture. In most modern forms of large testing machines the loads are applied by means of hydraulic pressure acting on a piston or plunger to which one end of the specimen is secured, and the stress is measured by connecting the other end to a lever or system of levers provided with adjustable weights. In small machines, and also in some large ones, the stress is applied by screw gearing instead of by hydraulic pressure. Springs are sometimes used instead of weights to measure the stress, and another plan is to make one end of the specimen act on a diaphragm forming part of a hydrostatic pressure-gauge (§ 23 below).

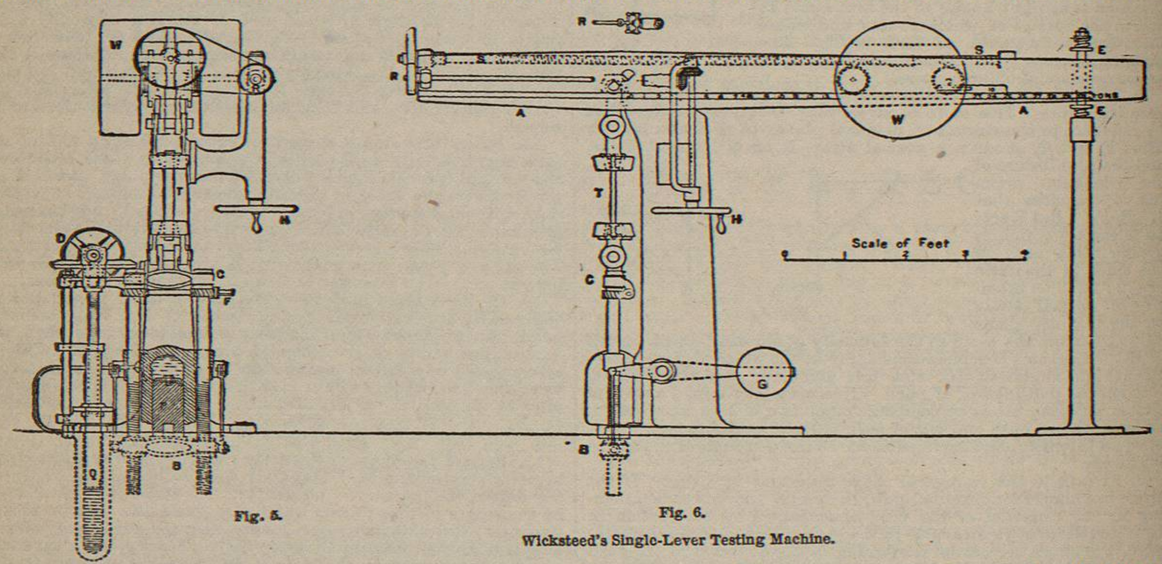

Fig. 5. Fig. 6.

Wicksteed's Single-Lever Testing Machine.

20. Figs. 5 and 6 show an excellent form of single-lever testing machine designed by Mr J. H. Wicksteed,[2] in which the stress is applied by an hydraulic plunger and is measured by a lever or steelyard and a movable weight. The illustration shows a 30-ton machine, but machines of similar design have been built to exert a force of 100 tons or more. AA is the lever, on which there is a graduated scale. The stress on the test-piece T is measured by a weight W of 1 ton (with an attached vernier scale), which is moved along the lever by a screw-shaft S; this screw-shaft is driven by a belt from a parallel shaft R, which takes its motion, through bevel-wheels and a Hooke's joint in the axis of the fulcrum, from the hand-wheel H. (The Hooke's joint in the shaft R is shown in a separate sketch above the lever in fig. 6.) The holder for the upper end of the sample hangs from a knife-edge three inches from the fulcrum of the lever. The lower holder is jointed to a crosshead C, which is connected by two vertical screws to a lower crosshead B, upon which the hydraulic plunger P, shown in section in fig. 5, exerts its thrust. G is a counterpoise which pushes up the plunger, when the water is allowed to escape. Hydraulic pressure may be applied to P by pumps or by an accumulator. In the present instance it is applied by means of an auxiliary plunger Q, which is pressed by screw gearing into an auxiliary cylinder. Q is driven by a belt on the pulley D. This puts stress on the specimen, and the weight W is then run out along the lever so that the lever is just kept floating between the stops E, E. Before the test-piece is put in, the distance between the holders is regulated by means of the screws connecting the upper and lower crossheads C and B, these screws being turned by a handle applied at F. Fig. 7 is a section of one of the holders, showing how the test-piece T is gripped by serrated wedges. The knife-edges are made long enough to prevent the load on them ever exceeding 5 tons to the linear inch.

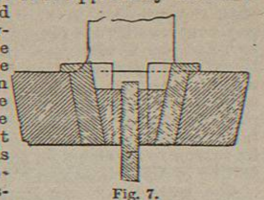

Fig. 7.

21. Another example of the single-lever type is the Werder testing machine, much used on the continent of Europe. In it the specimen is horizontal; one end is fixed, the other is attached to the short vertical arm of a bell-crank lever, whose fulcrum is pushed out horizontally by an hydraulic ram.[1] In many other testing machines a system of two, three, or more levers is employed to reduce the force between the specimen and the measuring weight. Probably the earliest machine of this class was that of Major Wade,[2] in which one end of the specimen was held in a fixed support, and the stretch was taken up by screwing up the fulcrum plate of one of the levers. In most multiple-lever machines, however, the fulcrums are fixed, and the stress is applied to one end of the specimen by hydraulic power or by screw gearing, which of course takes up the stretch, as in the single-lever machines already described. Mr Kirkaldy, who was one of the earliest as well as one of the most assiduous workers in this field, applies in his 1,000,000 ℔ machine a horizontal hydraulic press directly to one end of the horizontal test-piece. The other end of the piece is connected to the short vertical arm of a bell-crank lever; the long arm of this lever is horizontal, and is connected to a second lever to which weights are applied. In some of Messrs Fairbanks's machines the multiple-lever system is carried so far that the point of application of the weight moves 24,000 times as far as the point of attachment to the test-piece. The same makers have employed a plan of adjusting automatically the position of the measuring weight, by making the scale lever complete an electric circuit when it rises or falls so that it starts an electric engine which runs the weight out or in.[3] Generally the measuring weight is adjusted by hand. In some, chiefly small, machines, the weight adjusts itself by means of another device. It is fixed at one point of a lever which is arranged as a pendulum, so that, when the test-piece is pulled by force applied at the other end, the pendulum lever is deflected from its originally vertical position and the weight acts with increasing leverage.

Multiple-lever machines have the advantage that the measuring weight is reduced to a conveniently small value, and that it can be easily varied to suit test-pieces of different strengths. On the other hand, their multiplicity of joints makes the leverage somewhat uncertain and increases friction. Another drawback is the inertia of the working parts. It is impossible to avoid oscillations of the levers; and, to prevent them from producing important errors in the recorded stress, the inertia of the oscillating system should be minimized. In a testing machine in which the specimen is directly loaded the inertia is simply that of the suspended weight M. In a lever machine, which multiplies the weight n times, the weight applied to the lever is reduced to M/n, but its inertia, when referred to the test-piece, is $(M/n) \times n^2$ or Mn. The inertia which is effective for producing oscillation is thus increased n times, so far as the weight alone is concerned, and this detrimental effect of leverage is increased by the inertia of the levers themselves. The effect will be more serious the greater is the leverage n.

22. Whitworth and others employ machines in which one end of the specimen is held in a fixed support; an hydraulic press acts on the other end, and the stress is calculated from the pressure of fluid in the press, this being observed by a pressure-gauge. Machines of this class are open to the obvious objection that the friction of the hydraulic plunger causes a large and very uncertain difference between the force exerted by the fluid on the plunger and the force exerted by the plunger on the specimen. It appears, however, that in the ordinary conditions of packing the friction is very nearly proportional to the fluid pressure, and its effect may therefore be allowed for with some exactness. The method is not to be recommended for work requiring precision, unless the plunger be kept in constant rotation on its own axis during the test, in which case the effects of friction are almost entirely eliminated.

23. In another important class of testing machines the stress (applied as before to one end of the piece, by gearing or by hydraulic pressure) is measured by connecting the other end to a flexible diaphragm, on which a liquid acts whose pressure is determined by a gauge. Fig. 8 shows a simple machine of this class (used in 1873 for testing wire by Sir W. Thomson and the late Prof. F. Jenkin). The wire is stretched by means of a screw at the top, and pulls up the lower side of a hydrostatic bellows; water from the bellows rises in the gauge-tube G, and its height measures the stress. Fig. 9 is Thomasset's testing machine, in which one end of the specimen is pulled by an hydraulic press A. The other end acts through a bell-crank lever B on a horizontal diaphragm C, consisting of a metallic plate and a flexible ring of india-rubber. The pressure on the diaphragm causes a column of mercury to rise in the gauge-tube D. The same principle is made use of in the testing machines of Chauvin and Marin-Darbel, Maillard,[4] and Bailey. It has found its most important application in the remarkable testing machine of Watertown arsenal, built in 1879 by the U.S. Government to the designs of Mr A. H. Emery. This is a horizontal machine, taking specimens of any length up to 30 feet, and exerting a pull of 360 tons or a push of 480 tons by an hydraulic press at one end. The stress is taken at the other end by a group of four large vertical diaphragm presses, which communicate by small tubes with four similar small diaphragm presses in the scale case. The pressure of these acts on a system of levers which terminates in the scale beam. The joints and bearings of all the levers are made frictionless by using flexible steel connecting plates instead of knife-edges. The total multiplication at the end of the scale beam is 420,000.[5]

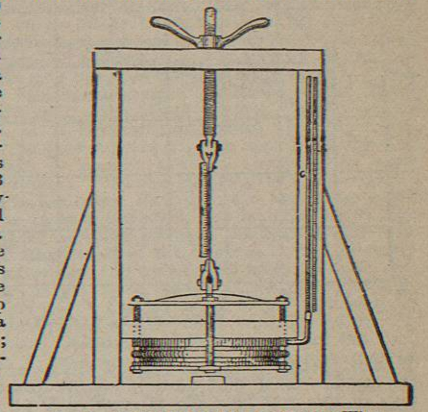

Fig. 8.—Hydraulic Machine for Testing Wire.

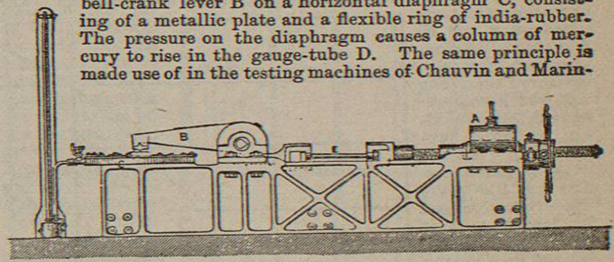

Fig. 9.—Thomasset's Testing Machine.

24. The results of tests are very commonly exhibited by means of stress-strain diagrams, or diagrams showing the relation of strain to stress. A few typical diagrams for wrought-iron and steel in tension are given in fig. 10, the data for which are taken from tests of long rods by Mr Kirkaldy.[6] Up to the elastic limit these diagrams show sensibly the same rate of extension for all the materials to which they refer. Soon after the limit of elasticity is passed, a point, which has been called by Prof. Kennedy the yield-point, is reached, which is marked by a very sudden extension of

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[1] French engineers usually estimate the permissible working stress as a certain fraction of the elastic strength (that is, of the stress which reaches the limit of elasticity), instead of estimating it as a certain fraction of the ultimate strength.

[2] *Proc. Inst. Mech. Eng.*, August 1882.

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[1] *Maschine zum Prüfen d. Festigkeit d. Materialen*, &c., Munich, 1882.

[2] *Report of Experiments on Metals for Cannon*, Philadelphia, 1856; also Anderson's *Strength of Materials*, p. 15.

[3] Abbott, *On Testing Machines*, New York, 1884, or *Van Nostrand's Engineering Mag.*, 1884.

[4] For descriptions of several of these machines, see a paper by MM. Denizeau and Lechien, *Mémorial de l'Artillerie et de la Marine*, 1883.

[5] See *Report of the U.S. Board appointed to test Iron, Steel, and other Metals*, 2 vols., 1881. For full details of the Emery machine, see *Report of the U.S. Chief of Ordnance*, 1883, appendix 24.

[6] *Experiments on the Mechanical Properties of Steel by a Committee of Civil Engineers*, London, 1868 and 1870.

the specimen. After this the extension becomes less rapid; then it continues at a fairly regular and gradually increasing rate; near the point of rupture the metal again begins to draw out rapidly.

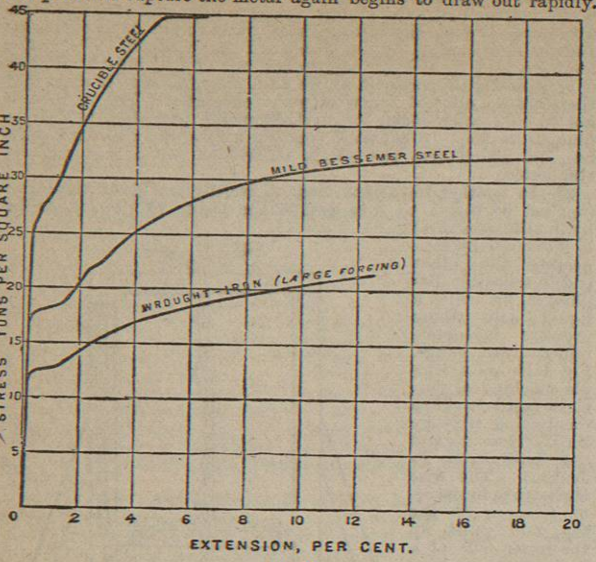

Fig. 10.

When this stage is reached rupture will occur through the flow of the metal, even if the load be somewhat decreased. The diagram may in this way be made to come back towards the line of no load, by withdrawing a part of the load as the end of the test is approached (§ 29 below).

25. Fig. 11 is a stress-strain diagram for cast-iron in extension and compression, taken from Hodgkinson's experiments.[1] The extension was measured on a rod 50 feet long; the compression was also measured on a long rod, which was prevented from buckling by being supported in a trough with partitions. The full line gives the strain produced by loading; it is continuous through the origin, showing that Young's modulus is the same for pull and push. (Similar experiments on wrought-iron and steel in extension and compression have given the same result.) The broken line shows the set produced by each load. Hodgkinson found that some set could be detected after even the smallest loads had been applied. This is probably due to the existence of initial internal stress in the metal, produced by unequally rapid cooling in different portions of the cast bar. A second loading of the same piece showed a much closer approach to perfect elasticity. The elastic limit is, at the best, ill defined; but by the time the ultimate load is reached the set has become a more considerable part of the whole strain. The pull curves in the diagram extend to the point of rupture; the compression curves are drawn only up to a stage at which the bar buckled (between the partitions) so much as to affect the results.

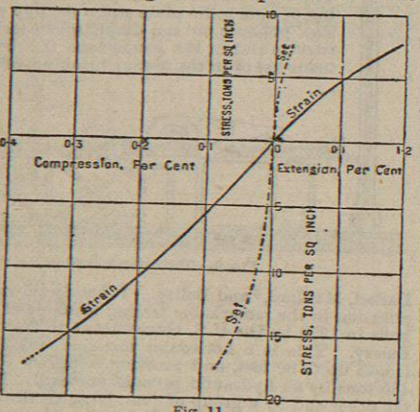

Fig. 11.

26. Testing machines are now frequently fitted with autographic appliances for drawing strain diagrams. When the load is measured by a weight travelling on a steelyard, the diagram may be drawn by connecting the weight with a drum by means of a wire or cord, so that the drum is made to revolve through angles proportional to the travel of the weight. At the same time another wire, fastened to a clip near one end of the specimen, and passing over a pulley near the other end, draws a pencil through distances proportional to the strain, and so traces a diagram of stress and strain on a sheet of paper stretched round the drum. Apparatus of this kind has been used by Messrs Fairbanks, Unwin, Aspinall, and others.[2] In Mr Wicksteed's autographic recorder the stress is determined by reference, not to the load on the lever, but to the pressure in the hydraulic cylinder by which stress is applied. The main cylinder is in communication with a small auxiliary hydraulic cylinder, the plunger of which is kept rotating to avoid friction at its packing. This plunger abuts against a spring, so that the distance through which it is pushed out varies with the pressure in the main cylinder. A drum covered with paper moves with the plunger under a fixed pencil, and is also caused to rotate by a wire from the specimen through distances proportional to the strain. The scale of loads is calibrated by occasional reference to the weighted lever.[3] In Prof. Kennedy's machine autographic diagrams are drawn by applying the stress to the test-piece through an elastic master-bar of larger section. The master-bar is never strained beyond its elastic limit, and within that limit its extension furnishes an accurate measure of the stress; this gives motion to a pencil, which writes on a paper moved by the extension of the test-piece.[4] In Prof. Thurston's pendulum machine for torsion tests, a cam attached to the pendulum moves a pencil through distances proportional to the stress, while a paper drum attached to the other end of the test-piece turns under the pencil through distances proportional to the angle of twist.[5]

27. The elastic extension or compression of a test-piece of ordinary dimensions is so small as to require for its measurement refined methods which are seldom employed in everyday practical testing. Measurements of this class must be made simultaneously on opposite sides of the test-piece, to guard against error through the bending of the piece. Microscopes and also various forms of micrometer calipers are used for the purpose.[6] A method capable of great delicacy, which has been used by Bauschinger[7] and others, is to measure the strain by light reflected from a pair of small mirrors attached to rollers which turn as the specimen extends or contracts. With apparatus of this kind it may be shown that iron, steel, or other materials with a well-defined yield-point begin to show a marked defect of elasticity at a somewhat lower stress. The true elastic limit comes considerably earlier in the test than the point which usually passes by that name.[8]

28. In testing a plastic material such as wrought-iron or mild steel it is found that the behaviour of the metal depends very materially on the time rate at which stress is applied. When once the elastic limit is passed the full strain corresponding to a given load is reached only after a perceptible time, sometimes even a long time. If the load be increased to a value exceeding the elastic limit, and then kept constant, the metal will be seen to draw out (if the stress be one of pull), at first rapidly and then more slowly. When the applied load is considerably less than the ultimate strength of the piece (as tested in the ordinary way by steady increment of load), it appears that this process of slow extension comes at last to an end. On the other hand, when the applied load is nearly equal to the ultimate strength, the flow of the metal continues until rupture occurs. Then, as in the former case, extension goes on at first quickly, then slowly, but, finally, instead of approaching an asymptotic limit, it quickens again as the piece approaches rupture. The same phenomena are observed in the bending of timber and other materials when in the form of beams. If, instead of being subjected to a constant load, a test-piece is set in a constant condition of strain, it is found that the stress required to maintain this constant strain gradually decreases. Viscosity

29. The gradual flow which goes on under constant stress—approaching a limit if the stress is moderate in amount, and continuing without limit if the stress is sufficiently great—will still go on at a diminished rate if the amount of stress be reduced. Thus, in the testing of soft iron or mild steel by a machine in which the stress is applied by hydraulic power, a stage is reached soon after the limit of elasticity is passed at which the metal begins to flow with great rapidity. The pumps often do not keep pace with this, and the result is that, if the lever is to be kept floating, the weight on it must be run back. Under this reduced stress the

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[1] *Report of the Commissioners on the Application of Iron to Railway Structures*, 1849.

[2] For descriptions of these and other types of autographic recorder, see a paper by Prof. Unwin, "On the Employment of Autographic Records in Testing Materials," *Jour. Soc. Arts*, Feb., 1886; also Prof. Kennedy's comprehensive paper, "On the Use and Equipment of Engineering Laboratories," *Min. Proc. Inst. C.E.*, 1886, which contains much valuable information on the whole subject of testing and testing machines.

[3] *Proc. Inst. Mech. Eng.*, 1886. An interesting feature of this apparatus is a device for preventing error in the diagram through motion of the test-piece as a whole.

[4] *Proc. Inst. Mech. Eng.*, 1886; also *Min. Proc. Inst. C.E.*, vol. lxxxviii., 1886, pl. 1.

[5] Thurston's *Materials of Engineering*, part ii. For accounts of work done with this machine, see *Trans. Amer. Soc. Civ. Eng.*, from 1876; also, *Report of* the American Board, cited above.

[6] See a paper by Prof. Unwin, *Phil. Mag.*, March, 1887.

[7] *Mitth. aus dem Mech.-Tech. Lab. in München*, Heft 5.

[8] *Cf.* Bauschinger, *loc. cit.*; Kennedy, *loc. cit.*; Jenny *Festigkeits Versuche*, Vienna, 1878.

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flow continues, more slowly than before, until presently the pumps recover their lost ground and the increase of stress is resumed. Again, near the point of rupture, the flow again becomes specially rapid; the weight on the lever has again to be run back, and the specimen finally breaks under a diminished load. These features are well shown by fig. 12, which is copied from the autographic diagram of a test of mild steel.[1]

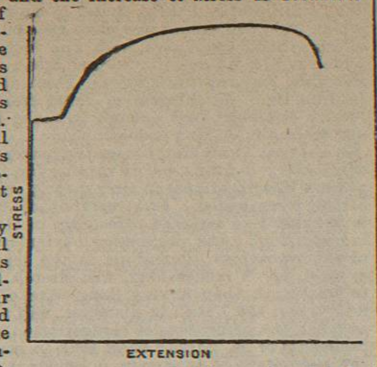

FIG. 12.—Autographic Diagram for a test of mild steel.

30. But it is not only through what we may call the viscosity of materials that the time rate of loading affects their behaviour under test. In iron and steel, and probably in some other metals, time has another effect of a very remarkable kind. Let the test be carried to any point *a* (fig. 13) past the original limit of elasticity. Let the load then be removed; during the first stages of this removal the material continues to stretch slightly, as has been explained above. Let the load then be at once replaced and loading continued. It will then be found that there is a new yield-point *b* at or near the value of the load formerly reached; up to this point there is little other than elastic strain. The full line *bc* in fig. 13 shows the subsequent behaviour of the piece. But now let the experiment be repeated on another sample, with this difference, that an interval of time, of a few hours or more, is allowed to elapse after the load is removed and before it is replaced. It will then be found that a process of hardening has been going on during this interval of rest; for, when the loading is continued, the new yield-point appears, not at *b* as formerly, but at a higher load *d*. Other evidence that a change has taken place is afforded by the fact that the ultimate extension is reduced and the ultimate strength is increased (*e*, fig. 13).

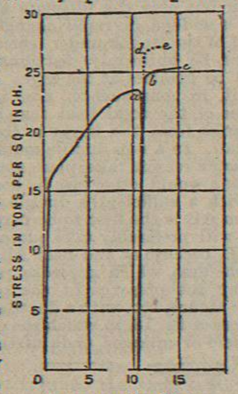

Fig. 13.

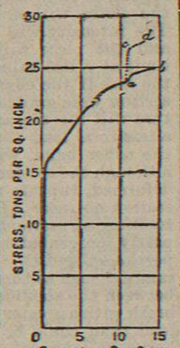

Fig. 14.

31. A similar and even more marked hardening occurs when a load (exceeding the original elastic limit), instead of being removed and replaced, is kept on for a sufficient length of time without change. When loading is resumed a new yield-point is found only after a considerable addition has been made to the load. The result is, as in the former case, to give greater ultimate strength and less ultimate elongation, Fig. 14 exhibits two experiments of this kind, made with annealed iron wire. A load of 23½ tons per square inch was reached in both cases; *ab* shows the result of continuing to load after an interval of five minutes, and *acd* after an interval of 45½ hours, the stress of 23½ tons being maintained during the interval in both cases.

32. It must not be supposed that in a material hardened by strain the elasticity is perfect up to the yield-points which are shown in fig. 13 at *b* and *d* or in fig. 14 at *c*. In experiments made for this article, it has been found that, after a piece of very soft iron wire has been hardened (as in fig. 14) by the continued application of a load which had caused stretching, if a small addition be made to the load (bringing it to a value between *a* and the new yield-point), although there is at first no apparent drawing out, nevertheless if time be given the wire begins again to draw, and a large amount of stretching at an increased pace may ensue. In this way wires have been broken with loads considerably short of those which would have been required had the process of loading, from the point *a* onward, been continued at a moderately rapid rate. A slow process of viscous deformation may in fact be occurring at the same time that the metal shows a quasi-elasticity with respect to rapid alteration of stress. Bauschinger's micrometric experiments have shown that after a piece has been hardened by rest the true limit of elasticity, or the point at which Hooke's law begins to fail, comes far short of the yield-point. He has also shown that a long interval of rest after the set has taken place produces a slow rise of the true limit of elasticity,[2] apparently a slower rise than the lapse of time causes in the yield-point itself.

33. In the testing of iron and steel the time during which any state of (pull) stress (exceeding the original elastic limit) exists affects the result in two somewhat antagonistic ways. It augments extension, by giving the metal leisure to flow. This may be called the viscous effect. But, on the other hand, it reduces the amount of extension which subsequent greater loads will cause, and it increases the amount of load required for rupture in the way which has just been described. This may be called the hardening effect. When a piece is broken by continuous gradual increment of load, these two effects are occurring at all stages of the test. If the viscous effect existed alone, or if the hardening effect were small, the material would show to greater advantage as regards elongation, and to less advantage as regards ultimate strength, the more slowly the load were applied. Tin and lead may be cited as materials for which this is the case. But when the hardening effect is relatively great, as in iron and steel, the material shows less elongation and a higher breaking strength the more slowly it is tested. An excellent illustration of this is given by the following experiment of Mr Bottomley. Pieces of iron wire, annealed and of exceptionally soft quality, when loaded at the rate of 1 ℔ in 5 minutes, broke with 44¼ ℔ and stretched 27 per cent. of their original length. Other pieces of the same wire, loaded at the rate of 1 ℔ in 24 hours, broke with 47 ℔ and stretched less than 7 per cent.[3] Again, it has been found that an excessively rapid application of stress (by the explosion of gun-cotton) makes soft steel stretch twice as much as in ordinary testing.[4] The case is very different, however, if the material has been previously hardened by strain. It does not appear that such variations in the rate of loading as are liable to occur in practical tests of iron or steel have much influence on the extension or the strength, great as the effects of time are when the metal is loaded either much more slowly or much more quickly. In fig. 15 the results are shown of tests of two similar pieces of soft iron wire, one loaded to rupture in 4 minutes and the other at a rate about 5000 times slower.

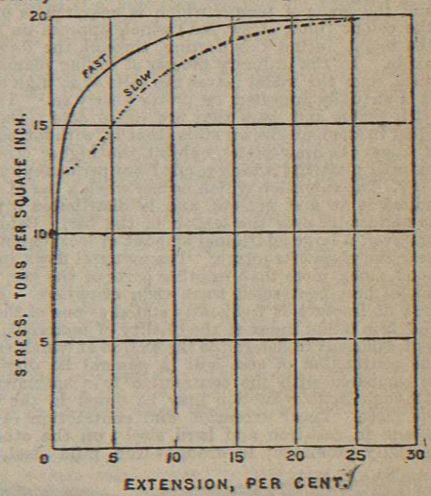

Fig. 15.

34. The hardening effect which intervals of rest from load or of constant load produce, once the primitive elastic limit is passed, has been examined by Beardsley,[5] Thurston,[5] Bauschinger,[6] Ewing,[7] and others. The effect of even a few minutes' pause is perceptible, an hour or two of constant stress has a very marked influence, and after 24 hours or so there appears to be little further hardening. The American Board found that iron bars, previously stressed to about 50,000 ℔ per square inch, gained in strength, by intervals of rest from stress, to the extent of about 8 per cent. in one day, 16 per cent. in three days, and 18 per cent. in six months.[8]

35. It may be concluded that, when a piece of metal has in any way received a permanent set by stress exceeding its limits of

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[1] The increase of strain without increase of stress, which goes on without limit when a test-piece under tension approaches rupture, is a special case of the general phenomenon of "flow of solids," which has been exhibited, chiefly for compressive stresses, in a series of beautiful experiments by Tresca (*Mémoires sur l'Écoulement des Corps Solides*, also *Proc. Inst. Mech. Eng.*, 1867 and 1878).

[2] *Mitth. aus dem Mech.-Tech. Lab. in München*, Heft 13, 1886.

[3] *Proc. Roy. Soc.*, 1879, p. 221. See also ELASTICITY, § 80.

[4] See remarks by Col. Maitland, *Min. Proc. Inst. C.E.*, vol. lxxvi. p. 104.

[5] See *Report of the U.S. Board on Tests of Metals*, vol. i. section 4.

[6] *Loc. cit.*

[7] *Proc. Roy. Soc.*, June 1870. The autographic diagrams given in figs. 13 and 14 are taken from these tests.

[8] *Loc. cit.*, p. 111.