

1855; *Ulrich von Hutten*, 3 vols., 1858-60, 4th ed., 1878; *H. S. Reimarus*, 1862). With this last-named work (see REIMARUS) he returned to theology, and two years afterwards (1864) published his *Leben Jesu für das Deutsche Volk* (4th ed., 1877). It failed to produce an effect comparable with that of the first *Life*, but the replies to it were many, and Strauss answered them in his pamphlet *Die Halben und die Ganzen* (1865), directed specially against Schenkel and Hengstenberg. His *Christus des Glaubens und der Jesus der Geschichte* (1865) is a severe criticism of Schleiermacher's lectures on the life of Jesus, which were then first published. From 1865 to 1872 Strauss resided in Darmstadt, where he made the personal acquaintance of the princess Alice and the crown-princess of Germany, receiving from both ladies many marks of esteem. In 1870 he published his lectures on *Voltaire* (3d ed., 1872), which were written for the princess Alice and delivered before her. In the works of these years it seemed that the truth of Christianity had become still more problematic to Strauss, and this was more obvious than ever in his next and last important work, his confession, and final summary answer to the four great questions—Are we Christians? Have we still religion? What is our conception of the world? How are we to regulate our lives? (*Der Alte und der Neue Glaube*, 1872, 11th ed., 1881, English translation by M. Blind, 1873). The work produced a greater sensation than his first *Life of Jesus*, and not least amongst Strauss's own friends, who wondered at his one-sided view of Christianity, his professed abandonment of all spiritual philosophy, the strange inconsistencies of his thought, his scientific credulity, and the offensive form of his negations. To the fourth edition of the book he added a *Nachwort als Vorwort* (1873). The same year symptoms of a fatal malady appeared, and death followed February 7, 1874. Though his last book renounced in almost frivolous language the hope of immortality, he read Plato's *Phædo* in the Greek during his last days, and Zeller says "his friends bade him adieu with feelings such as Plato has described at the end of that dialogue."

Strauss's mind was almost exclusively analytical and critical, without depth of religious feeling, or philosophical penetration, or historical sympathy. His work was accordingly rarely constructive, and, save when he was dealing with a kindred spirit, he failed as an historian, biographer, and critic, strikingly illustrating Goethe's profoundly true principle that loving sympathy is essential for productive criticism. His first *Life of Jesus* was directed against not only the traditional orthodox view of the Gospel narratives, but likewise the rationalistic treatment of them, whether after the manner of Reimarus or that of Paulus. The mythical theory that the Christ of the Gospels, excepting the most meagre outline of personal history, was the unintentional creation of the early Christian Messianic expectation he applied with merciless rigour and mechanical inconsideration to the narratives. But his operations were based upon fatal defects, positive and negative. He held a narrow theory as to the miraculous, a still narrower as to the relation of the divine to the human, and he had no true idea of the nature of historical tradition, while, as C. F. Baur complained, his critique of the Gospel history had not been preceded by the essential preliminary critique of the Gospels themselves. With a broader and deeper philosophy of religion, juster canons of historical criticism, with a more exact knowledge of the date and origin of the Gospels, his rigorous application of the mythical theory with its destructive results would have been impossible. In his second *Life of Jesus*, though conceding something to C. F. Baur, he adheres substantially to his mythical theory, while he seeks to make good one defect of the first *Life* by supplying a previous examination of the Gospels. But this examination shows little independent research, being scarcely more than the adoption of the conclusions of C. F. Baur and his earlier disciples. Another advance on the first work is the addition of a sketch of the historical facts of the life of Jesus and of his religious character, but he adheres to his early limited and shallow view of the relation of the divine and the human, and still fails to apprehend the true mission of the founder of the Christian religion. But the estimate of the religious mission of Jesus, and of the historical trustworthiness of the Gospels, is far higher in this *Life* than the final one in *Der Alte und der Neue Glaube*. As in his philosophical development he exhibited waver-

ing uncertainty, so it is impossible to reconcile his views of Christ and Christianity at different periods of his life. Some of the expressions of his last book in this respect are in glaring contrast with the positions he maintained in earlier years.

Strauss's works are published in a collected edition in 12 vols., by Zeller, Bonn, 1876-78, without his *Christliche Dogmatik*. On his life and works see Zeller's *David Friedrich Strauss in seinem Leben und seinen Schriften*, Bonn, 1874; A. Hausrath's *D. F. Strauss und die Theologie seiner Zeit*, 2 vols., Heidelberg, 1876-78; his own essay on *Julius Kerner*; F. J. Vischer's *Kritische Gänge*, 1. 3. Karl Schwarz, *Zur Geschichte der neuesten Theologie*, 4th ed., 1869; Heinrich Lang, *Religiöse Reden*, vol. II.; Dörner, *Geschichte der protestantischen Theologie*, 1876; Nippold, *Handbuch der neuesten Kirchengeschichte*, 1868; J. H. Scholten, "Strauss and Christianity," in *Theological Review*, 1874, Jan. and April; Hase, *Geschichte Jesu*, 1876, give critiques from different points of view of Strauss's theological works, particularly his *Lives of Jesus*. (J. F. S.)

STRAUSS, JOHANN (1804-1849), orchestral conductor and composer of dance-music, was born at Vienna, March 14, 1804. In 1819 he obtained his first engagement as a violinist in a small band then playing at the Sperl, in the Leopoldstadt. Shortly afterwards he joined Lanner, with whom he remained associated as deputy-conductor until 1825, when he organized a little band of fourteen performers on his own account. It was during the carnival of 1826 that Strauss inaugurated his long line of triumphs by introducing his band to the public of Vienna at the Schwan, in the Rossau suburb, where his famous *Taüberl-Walzer* (op. 1) at once established his reputation as the best composer of dance-music then living. Upon the strength of this success he was invited back to the Sperl, where he accepted an engagement, with an increased orchestra, for six years. Soon after this he was appointed kapellmeister to the 1st Bürger regiment, and entrusted with the duty of providing the music for the court balls; while the number of his private engagements was so great that he found it necessary to enlarge his band from time to time until it consisted of more than two hundred performers. In 1833 he began a long and extended series of tours throughout northern Europe, eventually visiting England in 1838. In Paris he associated himself with Musard, whose quadrilles became not much less popular than his own waltzes; but his greatest successes were achieved in London, where he arrived in time for the coronation of Queen Victoria, and played at seventy-two public concerts, besides innumerable balls and other private entertainments. The fatigue of these long journeys seriously injured Strauss's health; but he soon resumed his duties at the Sperl; and on May 5, 1840 he removed with his band to the Imperial "Volksgarten," which thenceforth became the scene of his most memorable successes. Those who enjoyed the privilege of hearing him conduct there could never forget the wonderful delicacy of the performance, over which the master presided with a quiet power which ensured the perfection of every minutest nuance. In 1844 Strauss began another extensive series of tours. In 1849 he revisited London, and, after his farewell concert, was escorted down the Thames by a squadron of boats, in one of which a band played tunes in his honour. This was his last public triumph. On his return to Vienna he was attacked with scarlet fever, of which he died, September 25, 1849.

Strauss was survived by three sons,—Johann (born 1825), Joseph (1827-1870), and Edward (born 1835), all of whom have distinguished themselves as composers of dance-music, and assisted in recruiting the ranks and perpetuating the traditions of the still famous band.

STRAUSS-DURCKHEIM, HERCULE (b. 1790, d. 1865), an eminent French entomologist, was the author of anatomical works of exquisite precision and fulness of detail. Two of these (his monographs of the anatomy of the cockchafer and of the cat) are permanent classics, of which the influence has aided greatly in raising the standard of zoological works.

STRAWBERRY (*Fragaria*). Apart from its interest as a dessert fruit (see HORTICULTURE, vol. xii. p. 276), the strawberry has claims to attention by reason of the pecu-

liarities of its structure and the excellent illustrations it offers of the inherent power of variation possessed by the plant, and of the success of the gardener in availing himself of this tendency. The genus *Fragaria* consists of a small number (three to four, according to Hooker) of species, native of the temperate regions of both hemispheres, as well as of mountain districts in warmer climes. The tufted character of the plant, and its habit of sending out long slender branches (runners) which produce a new bud at the extremity, are well known. The leaves are usually palmately three-parted, but the number of leaflets may be increased to five or reduced to one. While the flower has the typical Rosaceous structure, the so-called fruit is very peculiar, but it may be understood by the contrast it presents with the "hip" of the rose. In the last-named plant the top of the flower-stalk expands as it grows into a vase-shaped cavity, the "hip," within which are concealed the true fruits or seed-vessels. In the rose the extremity of the floral axis is concave and bears the carpels in its interior. In the strawberry the floral axis, instead of becoming concave, swells out into a fleshy, dome-shaped or flattened mass in which the carpels or true fruits, commonly called pips or seeds, are more or less imbedded but never wholly concealed. A ripe strawberry in fact may be aptly compared to the "fruit" of a rose turned inside out.

The common wild strawberry of Great Britain, which indeed is found throughout Europe and great part of North America, is *F. vesca*, and this was the first species brought under cultivation in the early part of the 17th century. Later on other species were introduced, such as *F. elatior*, a European species, the parent stock of the hautbois strawberries, and especially *F. virginiana* from the United States and *F. chiloensis* from Chiloe. From these species, crossed and recrossed in various manners, have sprung the vast number of different varieties now enumerated in catalogues, whose characteristics are so inextricably blended that the attempt to trace their exact parentage or to follow out their lineage has become impossible. It must suffice to say that the varieties at present cultivated vary in the most remarkable degree in size, colour, flavour, shape, degree of fertility, season of ripening, liability to disease, and constitution of plant. Some, as previously stated, vary in foliage, others produce no runners, and some vary materially in the relative development of their sexual organs, for, while in most cases the flowers are in appearance hermaphrodite, at least in structure, there is a very general tendency towards a separation of the sexes, so that the flowers are males or females only as to function, even although they may be perfect in construction. This tendency to dioecism is a common characteristic among *Rosaceæ*, and sometimes proves a source of disappointment to the cultivator, who finds his plants barren where he had hoped to gather a crop. This happens in the United States more frequently than in Britain, but when recognized can readily be obviated by planting male varieties in the vicinity of the barren kinds. Darwin, in alluding to the vast amount of variability in the so-called "fruit,"—a change effected by the art of the horticulturist in less than three centuries,—contrasts with this variability the fixity and permanence of character presented by the true fruits, or pips, which are distributed over the surface of the swollen axis. The will and art of the gardener have been directed to the improvement of the one organ, while he has devoted no attention to the other, which consequently remains in the same condition as in the wild plant. Too much stress is not, however, to be laid on this point, for it must be remembered that the foliage, which is not specially an object of the gardener's "selection," nevertheless varies considerably.

STRAW MANUFACTURES. Straw forms the raw material of some not unimportant industries. It serves for the thatching of roofs, for a paper-making material, for ornamenting small surfaces as a "straw mosaic," for plaiting into door and table mats, mattresses, &c., and for weaving and plaiting into light baskets, artificial flowers, &c. These applications, however, are insignificant in comparison with the place occupied by straw as a raw material for the straw bonnets and hats worn by both sexes. Of the various materials which go to the fabrication of plaited head-gear the most important is wheat straw. It is only in certain areas that straw suitable for making plaits is produced. The straw must have a certain length of "pipe" between the knots, must possess a clear delicate golden colour, and must not be brittle. The most valuable straw for plaits is grown in Tuscany, and from it the well-known Tuscan plaits and Leghorn hats are made. The straw of Tuscany, specially grown for plaiting, is distinguished into three qualities,—*Pontederas Semone* being the finest, *Mazzuolo* the second quality, from which the bulk of the plaits are made, while from the third quality, *Santa Fiora*, only "Tuscan pedals" and braids are plaited. The wheat-seed for these straws is sown very thickly on comparatively elevated and arid land, and it sends up long attenuated stalks. When the grain in the ear is about half developed the straw is pulled up by the roots, dried in the sun, and subsequently spread out for several successive days to be bleached under the influence of alternate sunlight and night-dews. The pipe of the upper joint alone is selected for plaiting, the remainder of the straw being used for other purposes. These pipes are made up in small bundles, bleached in sulphur fumes in a closed chest, assorted into sizes, and so prepared for the plaiters. Straw plaiting is a domestic industry among the women and young children of Tuscany and some parts of Emilia. Tuscan plaits and hats vary enormously in quality and value; the plait of a hat of good quality may represent the work of four or five days, while hats of the highest quality may each occupy six to nine months in making. The finest work is excessively trying to the eyes of the plaiters, who can at most give to it two or three hours' labour daily. The exports of plaits and manufactured hats from Leghorn average in value £480,000 annually, about one half of the goods going to America.

The districts around Luton in Bedfordshire and the neighbouring counties have, since the beginning of the 17th century, been the British home of the straw-plait industry. The straw of certain varieties of wheat cultivated in that region is, in favourable seasons, possessed of a fine bright colour and due tenacity and strength. The straw is cut as in ordinary harvesting, but is allowed to dry in the sun before binding. Subsequently straws are selected from the sheaves, and of these the pipes of the two upper joints are taken for plaiting. The pipes are assorted into sizes by passing them through graduated openings in a grilled wire frame, and those of good colour are bleached by the fumes of sulphur. Spotted and discoloured straws are dyed either in pipe or in plait. The plaiters work up the material in a damp state, either into whole straw or split straw plaits. Split straws are prepared with the aid of a small instrument having a projecting point which enters the straw pipe, and from which radiate the number of knife-edged cutters into which the straw is to be split. The plaiting of straw in the Luton district formerly gave employment to many thousands of women and young children; but now vast quantities of plaits are imported at a very cheap rate from Canton in China. The result is that, while the Luton trade is extending, the number of persons it there gives occupation is greatly diminished. In 1871 about 50,000 persons

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.

3. In a solid body which is in a state of stress the direction of Normal stress at an imaginary surface of division may be normal, oblique, and 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

¹ One ton per sq. in. = 2240 lb per sq. in. = 1.011 kilos. per sq. mm.
² See ELASTICITY, vol. VII, p. 619.

STRENGTH OF MATERIALS

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 $\theta = 45^\circ$: planes inclined at 45° to the axis are called planes of maximum shearing stress; the intensity of shearing stress on them is $\frac{1}{2}p$.

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.

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 ABC (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.

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; and 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



Fig. 1.

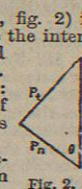


Fig. 2.

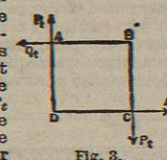


Fig. 3.

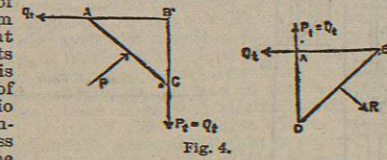


Fig. 4.

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 1678.

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 moduli applicable to other modes of stress. Since $E = p/\delta l$, 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 moduli 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 $E = \frac{9CK}{3K + C}$ and $\sigma = \frac{2(3K + C)}{3K - 2C}$

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

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

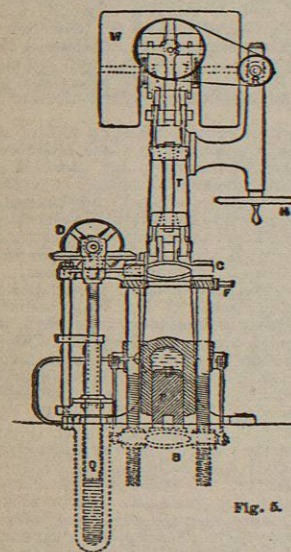


Fig. 5.

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

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.

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; and 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,

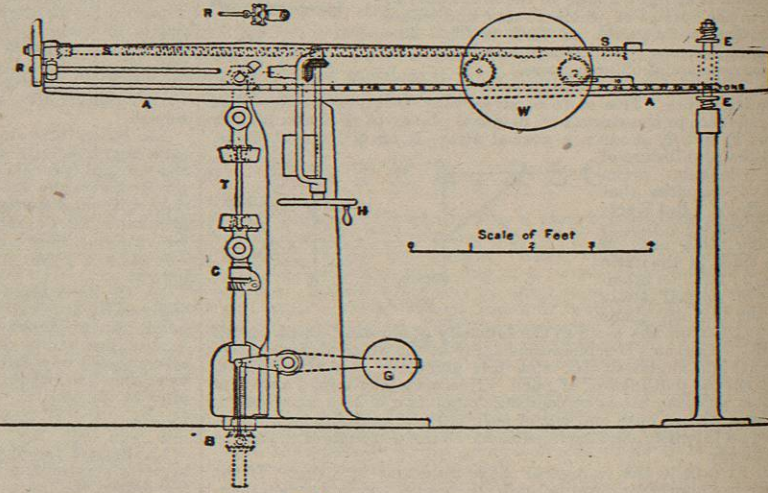


Fig. 6.

Wicksteed's Single-Lever Testing Machine.

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).

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

² Proc. Inst. Mech. Eng., August 1882.

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 cross-head C, which is connected by two vertical screws to a lower cross-head 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

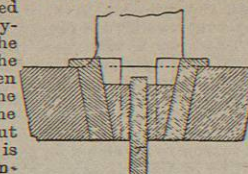


Fig. 7.

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 cross-heads 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.

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 lb 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

¹ Maschine zum Prüfen d. Festigkeit d. Materialien, &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.

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

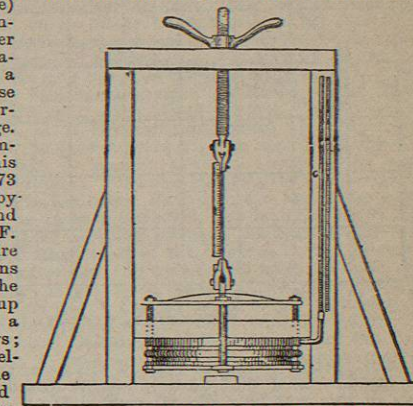


Fig. 8.—Hydraulic Machine for Testing Wire.

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-

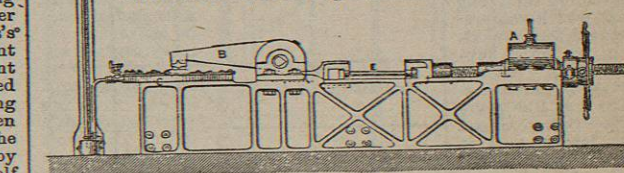


Fig. 9.—Thomasset's Testing Machine.

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

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

⁴ For descriptions of several of these machines, see a paper by MM. Denizau and Lechien, *Mémoires 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.