Stability of Structures*

By J. S. Wilson

THE meaning of stability is not easy to define. In dynamics and mechanics we have stability of steady motion and stability of equilibrium, of position and of friction. To the civil engineer the word is usually applied to the power of a structure to withstand for an indefinite time all the loads and forces that may be brought to bear on it.

The most stable structure ever built is probably the Great Pyramid of Egypt. It consists of large blocks of limestone carefully shaped and piled together to the height of 480 ft. on a base measuring 830 ft. square. Another example of a great pile: a pile of bricks laid one on another, was a tall chimney such as the celebrated one at St. Rollox in Glasgow. This had a height of 435 ft., and at its base a diameter of 40 ft. It was pulled down a few years ago after having stood since 1842. A masonry dam built across a valley to impound water is a form of structure the stability of which must be beyond question, as failure would lead to disastrous flooding. Then we have the arch, the most beautiful and fascinating form of construction invented by man. In its simple form we have arches of imposing size and graceful stability across rivers, while in cathedrals and other great buildings we have it in the groin, dome and buttress.

In each of these examples, strength and stability depend mainly on the resistance to compression offered by stone or brick. A complementary form of structure, dependent on the resistance to rupture by the pulling asunder of its parts, is the suspension bridge, the stability of which depends almost entirely on the tensile resistance of the chains or cables. The greatest structure of this form is undoubtedly the George Washington Bridge over the Hudson River, New York, with its span of 3,400 ft.

In most iron and steel structures the resistance of the material to both tension and compression contributes to their stability in equal proportions, as is found in the great girder and cantilever bridges. Reinforced concrete, in which the great strength of concrete to resist compression is combined with the power of steel to resist tension, owes its development largely to the facility with which it can be built and shaped. Tunnels of masonry or brickwork, and cast-iron lined tube tunnels, subject to the pressure of great depths of earth, are forms of structure the stabilities of which are not easy to calculate.

There are two sides to all problems in stability; the first depends on applied mechanics, the second on the regulation of stresses to get an economical use of material. Progress in the second during the last fifty years has not been so great as in the first, to which my remarks refer more particularly. To fix the directions of, and arrange for the balance of, loads and forces, the conception of action along lines was introduced at an early stage. The position of such a line, with respect to the boundary of a member offering resistance, governs the distribution and intensity of stresses in the material. In estimating the intensity of stress, the position of the line in a lamina of the part under consideration is usually considered, and in it the distribution of the stress follows the 'trapezium law', which is a particular case of Galileo's solution of the beam problem. Thus if the line representing the centre of action of the load or thrust is on the centre of the section of the member, the stress intensity would be the same throughout the section. If the line of action is off the centre, then the intensity is increased on the side towards which the line has moved. The diagram representing the distribution of stress is a trapezium, the centre of gravity of which is on the line of action.

In a pier or buttress which supports and at the same time resists the thrust of an arch, the line representing the resultant of the weight and thrust of the arch is deflected downwards by the weight of the buttress, and the buttress may be so shaped that the deflected line is everywhere near the centre giving a uniform intensity of stress in the masonry, and uniform pressure on the ground below the foundations. On the other hand, the balance may not be so good, and the line may be towards the outer side of the buttress, giving high concentration in the masonry and ground.

Historically, the problem of the masonry arch is extremely interesting. The arch form of construction has been known for thousands of years, and several magnificent arches built by the Romans are still in a very good state. Real progress in the theory of the design and strength of the arch is comparatively recent.

In a masonry arch the line of thrust might occupy one of a variety of positions any of which would satisfy the requirements of equilibrium. For the purposes of design or estimating stability, some particular line must be chosen, and this can only be done by making assumptions, the validity

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of which must have regard to the method of construction and the probable conditions of stress in the masonry. One assumption relates to the position of the line of thrust at the crown or springings. Since 1870, one of the advances made has been the introduction of definite hinges, at the crown or at the springing level, or at both places, to ensure the line of thrust passing through those points. These hinges render the problem of strength and stability much more definite, but with respect to arches without hinges the position is unchanged, although much has been done by comparing and analysing existing structures. In the monumental work by Sejourne[1], particulars are given of all arches of appreciable size throughout the world: details of construction are given, and the proportions are analysed and compared.

Up to the first half of the nineteenth century, knowledge of the strengths and characteristics of materials, and of the branch of engineering science now known as 'applied mechanics', was not sufficient to establish or disprove the accuracy of various theories relating to the design or stability of a masonry arch then in vogue or from time to time propounded; efforts to make progress in the problem depended almost as much on dialectics as on mechanical principles.

Throughout a long period in the eighteenth and nineteenth centuries, mathematicians and others applied themselves to finding the exact form of the line of thrust that would ensure equilibrium in a mass of masonry bridging a void. The upper boundary of the mass was a horizontal surface representing the road surface and the lower one the intrados of the arch, shaped to conform to the line sought.

The shape of this arch of equilibrium was compared in great detail with those of the ellipse, cycloid, parabola, catenery and semi-circle or segment of a circle. Different writers strongly advocated one or other of these curves as being the true curve for an arch. The elaboration with which this was done seems remarkable, for many must have known that to build an arch to conform to a particular curve with the exactitude suggested is practically impossible. When the centering on which an arch is built is removed and the arch supports itself, the compression of the mortar in the joints and of the voissoir stones allows the arch to drop an amount which is quite sufficient to alter the shape appreciably; thus the arches of Perronet's famous bridge at Neuilly dropped, on decentering, enough to alter the radius curvature at the crown from 150 ft. to 244 ft., and if intended to be elliptical, it might have conformed actually more closely to a cycloid.

For the longest spans, reinforced concrete has now superseded masonry; but fine masonry arches of 300-ft. span have been built. The construction of spans of increasing length has been made possible by improved technique in building. To avoid high stresses arising at the springing and key stone, as a result of the settlement or elastic deformation of the centering, as weight is added during building, and as a consequence of the initial deformation of the arch itself when the centering is removed, gaps are left in the arch, and special forms of construction are now introduced to act as temporary hinges, so that when the bridge is completed and the gaps filled in, the position of the line of thrust is fairly definitely known. In reinforced concrete arches, either permanent hinges of steel are introduced or else all the reinforcing bars are drawn together at the critical points to form a temporary hinge, and the surrounding concrete is filled in only on completion. Reinforced concrete arches with spans as great as 590 ft. have been constructed.

The stability of a masonry dam is a problem that has exercised the minds of engineers and mathematicians for many years. The failure of the Bouzey dam in France in 1895 gave prominence to the problem. The Bouzey dam was straight with a length of 1,720 ft., and the water held up had a maximum depth of about 40 ft. When the dam failed, the upper 30 or 35 ft. of its height for a length of 560 ft. was swept away, and the flood, passing down the valley, caused great havoc, and eighty-six people lost their lives.

Investigations after the disaster revealed many points of interest. In the original design, the maximum pressure on the masonry was the only factor considered in calculating its proportions. In the course of the investigations after the disaster it was shown that the resultant of the thrust combined with the weight of the masonry was so placed that a tensile stress of 1·3 tons per sq. ft. must have been imposed on the masonry. Laboratory tests proved that the maximum tensile strength of the masonry was only 60 per cent higher. In opposition to the theory that the parts that failed had overturned by virtue of this weakness, it was held by some that failure was by shearing; the shearing stress being calculated as 1·32 tons per sq. ft. by some, and as 3·2 tons per sq. ft. by others.

Rankine, in 1871, had recommended that no horizontal joint in a dam should be expected to withstand any tensile stress; in other words, there should be no uplifting tendency. After the Bouzey disaster it was considered advisable that at the upstream face there must always be a definite compressive stress, and the French Government introduced the regulation that on horizontal joints there should be a vertical compressive stress at the water face equal to not less than the water pressure at the joint. Such compression in the masonry would tend to prevent access of water to any joint or crack.

The late Sir Benjamin Baker, in 1904–5, at the time when I was his chief assistant, was faced with the problem of raising the Assuan dam. (At present the dam is being raised a second time.) The investigations after the disaster in France had shaken confidence in the accepted method of gauging the stability of a dam, and in 1904 a memoir was published entitled "Some Disregarded Points in the Stability of Masonry Dams", by Prof. Karl Pearson and Mr. Atcherley. By mathematical investigation, the authors concluded that although a dam might satisfy the usual conditions regarding the stresses on horizontal planes, it might still be subjected to dangerous tensile stresses on vertical planes in the vicinity of the downstream toe. That conclusion seemed most unlikely to engineers interested in the subject, but however incredible it might seem, it demanded attention as coming from so eminent a mathematician. In arriving at their results, the authors of the memoir based their calculations on an assumed law governing the distribution of shearing stress across the base. The unsatisfactory state of affairs could only be cleared up by determining the distribution of sheer and other stresses.

Jointly with my friend the late William Gore, I made an attempt to do this, and we embarked on a series of elaborate experiments with india-rubber models.

Our investigations were described and discussed at the time at the Institution of Civil Engineers[2] and in *Engineering*[3], in which journal there was correspondence on the subject.

The models were made of slabs of rubber 1 in. thick with a smooth white surface, and shaped to represent the transverse section of a dam. The model was strained by weights carefully adjusted to represent the water pressure against the face and the weight of the masonry, on the assumption that the masonry had a specific gravity of 2·25. The model was divided into sections, and the 'masonry weights' were hung on transverse pins put through the rubber. Plates pulled by cords against the water face represented the water pressure. To ensure the exact relative positions of the loads, the model was so shaped that when fully strained it had the correct profile. A network of lines was ruled on the rubber, and large-sized photographs on plate-glass were taken under the strained and unstrained conditions. Corresponding lengths on the two negatives could be measured accurately, and from them the strains and stresses were calculated. The intensity of shear at various points was measured by comparing angles on the two plates. Our investigations enabled us to plot curves of stress-distribution on section lines at various heights. The curves were of quite definite shape. We found no evidence of the reputed tensile stress at the downstream toe. The shear stress diagram was practically a triangle with the maximum at the downstream edge, and the vertical stress distribution agreed substantially with the 'trapezium law'.

These experiments helped materially to clear up the situation and to re-establish confidence in the method that had been in general use for estimating the stability of masonry dams.

During the last few years, investigations of problems relating to the design of large concrete dams and curved dams have been made in the United States. The influence of heat, both natural and that generated by the setting of cement, on stresses and stability, has received much attention. In these gigantic structures, monolithic construction and the use of too large masses of concrete has been found accountable for serious cracking.

The suspension-bridge or 'philosopher's bridge', as it has been called, is a fascinating type of structure. In the course of the development of its design and stability there have been some astonishing occurrences. In its most elementary form, the suspension-bridge formed of strong flexible climbing stems or roots has been used by primitive peoples for centuries. Examples made of wrought iron appear to have been in existence in the eighteenth century. At the beginning of the nineteenth century the chains, which were made up with several links side by side, connected with common hinge pins, were of uniform strength throughout their length, and the road or platform was suspended by vertical rods. Within its limitations, this was a satisfactory form of construction. In a bridge which carries a series of loads on a flexible chain, the loads and the chains are only in equilibrium when the chain assumes an appropriate shape, and to support any additional weight or rearrangement of weights the chain changes its shape slightly. With a moving load, the tendency of the platform of a suspension-bridge to undulate with the passage of the load has handicapped the development of this type of bridge. An early attempt to use it for a railway proved a complete failure.

Telford's famous bridge across the Menai Straits, with a span of 570 ft., completed in 1826, is of the simple suspension type. At first the platform was too flexible and caused anxiety, but that part was altered and made stiffer. The bridge is still in service, and is standing proof that in principle and construction it was sound. A few years later, a supposed improvement, the 'taper chain' bridge, was introduced with the object of reducing the amount of iron required. The principle was unsound, and failures led to the suspension type of bridge being regarded with suspicion for many years.

Several suspension-bridges, built before 1836, are still in use. In all these the chains are of uniform strength throughout, and the whole weight of the bridge is suspended from them.

The flexibility of these bridges under heavy moving loads is a source of trouble, and of wear and tear of the platforms. Nevertheless, when the chains are pulled by the loads into a line of equilibrium, so long as the anchorages are secure and the towers are sound, the stability depends solely on the tensile strength of the chain, and under these conditions almost all suspension-bridges have a substantial margin of strength or stability.

One of the early suspension-bridges still in use is that across the Thames at Marlow, built by W. Tierney Clark, in 1829. I examined and reported on this bridge some years ago and found it in a remarkably good state. In the development of the stability of suspension-bridges this one is of particular interest, for it was the first built with stiffening girders. The ends of the cross girders in this bridge are all stiffly connected by parapets made in the form of girders, and any cross girders on which a heavy load might rest cannot deflect the suspension chain, as it would do if the parapet girders were not there.

In the modern suspension-bridge the stiffening girder is as important a feature as the chain or cable, and its introduction has made it possible to construct the gigantic bridges in the United States. The interaction of the stiffness or flexibility of the girder with the curvature of the suspension cable is the governing factor in the stability of the modern suspension-bridge.

The latest example of suspension-bridge with its span of 3,400 ft. and others of more than 1,500 ft. compare with Telford's of 570 ft. and the others of 50–200 ft. Cables composed of thousands of steel wires, four times as strong as iron, laid side by side to form cables 3 ft. in diameter, take the place of the iron chains ; and the flexible timber platform, so easily deformed by moderate moving loads, is now replaced by deep steel stiffening girders with upper and lower decks providing double tracks for both electric railways and street trams and road width for many cars.

[1] Paul Séjourné, "Grandes Voutes", 1913–1916.

[2] *Minutes of Proceedings Inst. C.E.*, **172**; 1907–8.

[3] *Engineering*, 1905, 1907. Also NATURE, Jan. 30, 1908.

International Physiological Congress

MEETING IN THE U.S.S.R.

THE fifteenth International Physiological Congress met, under the presidential direction of Prof. I. P. Pavlov, in Leningrad and Moscow on August 8–18. The gathering proved of unusual interest, especially from the social point of view. The members, numbering more than eight hundred foreigners and about five hundred Russians, were given an opportunity to see something of the mechanism of the communistic regime. The several receptions and banquets in the old royal palaces gave the members a glimpse of the almost oriental splendour which surrounded the ruling class under the Czars.

The Russian National Committee and the Soviet Government treated the Congress with unique hospitality. From the initial, informal reception in the magnificent Marble Hall of the Ethnographical Museum in Leningrad, to the final banquet in the Grand Palace of the Kremlin, and the aviation display on the outskirts of Moscow, the entertainments arranged for the Congress were consistently lavish.

The three plenary sessions, at which five scientific papers were read by well-known physiologists, were the outstanding occasions of the Congress. The first plenary session was opened by Prof. Pavlov, who gave the Congress a stirring welcome. The paper delivered at this time by Prof. Walter B. Cannon (Boston) was entitled "Some Implications of the Evidence for Chemical Transmission of Nerve Impulses". It constituted an outline of present knowledge in the field of neurohumours. Both the sympathetic nervous system and its chemical representative, adrenalin, act in a widespread manner. Acetylcholine is the chemical representative of the parasympathetic nervous system. Unlike adrenalin, acetylcholine is very unstable. Thus its action is limited to the region in which it is produced. The action of the parasympathetic nervous system is similarly localised.

The evidence for the existence of two adrenalin-like or adrenergic neurohumours was cited. These were named sympathin E (excitatory) and sympathin I (inhibitory). Langley suggested this concept in 1905. He further believed that the differentiation probably takes place in the effector cells, and this is to-day unrefuted but unproved. Possibly the sympathetic mediator, acetylcholine, has excitatory and inhibitory forms. At present,