STRUCTURES AND THE APPLIED SCIENTIST

Inaugural Lecture of the Professor of Civil Engineering delivered at the College on March 8, 1955

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M.A., PH.D.

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PRINTED IN GREAT BRITAIN

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THOSE who are called upon to deliver inaugural lectures seldom approach the event without considerable misgivings, and yet there was one aspect of my task which I anticipated with nothing but pleasure. Nearly six months have passed since my arrival in Swansea, and this enables me to say how enjoyable it has been to be absorbed into the vigorous and stimulating intellectual atmosphere of the College. I can also express the appreciation of my wife and myself of the warm welcome which we have been accorded by the friendly society of both the College and the town of Swansea. And if you are tempted to be unduly critical of the content of my address, let at least a portion of the blame fall on the fascinations of Caswell Bay and the seductiveness of the Gower coast, which can lure even the sternest of us from the path of duty.

The creation of a new Chair of Civil Engineering within the Engineering Department of the College is but another manifestation of the growing demand for technologists in Great Britain. Civil Engineering is by no means a new departure at Swansea, for its study has been fostered by Dr. Fordham while a whole generation of students have profited by his enthusiasm and wise counsel. It is therefore appropriate to pay him a tribute on this occasion, and I should like also to express the hope that he may enjoy the long and happy retirement which he so richly deserves.

The appointment to a Chair carries with it many responsibilities, but my burden is lessened by virtue of the fact that the basic organization of the Engineering Department has continued to be carried out by Professor

Kastner, who as befits a mechanical engineer has created well-oiled machinery for the purpose. It is sad to record that we shall be losing him at the end of the session, for his appointment to a Chair at King's College, London, was recently announced. I should like to take this opportunity of wishing him every success in his new venture. In his inaugural lecture, delivered five years ago, Professor Kastner began by discussing the education of engineers, and so although this topic naturally forms the basis of many inaugural addresses I felt that a different subject was called for on this occasion. I have therefore chosen to sketch the growth of the relationship between applied scientists and structural engineers in recent times. Collaboration between applied scientists and engineers is the key to the most rapid progress in all branches of technology, and by examining its development in a restricted field we may endeavour to see how it can be brought to the highest degree of efficiency in the future.

It is often mistakenly supposed that the terms 'applied scientist' and 'engineer' are synonymous, but this is far from the truth. The engineer is concerned with the actual design and fabrication of useful products. In the preparation of designs he is usually bound by Codes of Practice, which embody the accumulated experience of the past and are essential in establishing reasonably uniform standards of safety throughout the country. In contrast the applied scientist, working at a university or perhaps one of the government research establishments, has the often self-imposed task of bringing scientific methods of study to bear on problems arising out of engineering practice. The problems which he selects are of fundamental scientific interest, but their solution may eventually lead to the evolution of more logical and economical methods of design which can be incorporated in the relevant Codes of Practice.

It is impossible in the space of a brief discourse to range over the complete field of structural engineering, and so I will restrict my discussion to the applied scientific work which has been carried out in connexion with steel-framed buildings and bridges. The first recorded example of the construction of a building in Britain in which the main framework was a steel skeleton was the erection of a warehouse building at Stockton-on-Tees in 1898. Buildings of this kind are now a commonplace, and in fact a steel skeleton is now being erected in Singleton Park as the framework of a new permanent college building. At first sight it seems absurd to suggest that the design of such a skeleton presents a problem of acute difficulty to the applied scientist, for it is evident that the current design practice results in structures which are adequate for their purpose. However, it is one thing to design a frame which will safely withstand the applied loads, but quite another matter to design the frame which will not only fulfil this function but is also the most economical in the use of steel. When a solution to the former problem had been found, the interest of engineers in this topic lapsed, but the latter problem is still engaging the attention of applied scientists, who have produced many fruitful results to date.

A steel framework consists basically of rows of horizontal beams supported at their ends on lines of vertical columns. The vertical loads on the floors are carried primarily on the beams, which transmit vertical thrusts down the columns to the ground. The most usual form of construction, which persists to the present day on account of its simplicity and the ease of erection, is to bolt the beams to the columns. The form of connexion which is adopted fastens the members together in a rather ill-defined manner. Two extreme forms of connexion can be envisaged. In the first type the connexion would be completely rigid, and in the second the beams would rest at each end on simple brackets. When in 1909 clauses were first incorporated in the London Building Act to regulate the use of steel in buildings, these clauses implied a simple design method in which the connexions were assumed to be so flexible that they approximated to the second or simple support type. This assumption was perhaps inspired more by expediency than by any other consideration, for its implication is that the bending of one beam is not transmitted through the connexions to the rest of the structure. The design procedure was thus greatly simplified, for each beam was in effect isolated from the rest of the structure and could therefore be designed very easily. The columns only carried the vertical loads from the beams, and rules for their design were formulated without much difficulty. These rules were based on extensions of the classical work of Euler, who had discussed in 1757 the problem of a long slender bar under compression. Euler showed that theoretically such a bar would remain straight until a critical load was reached, when the bar would suddenly bow outwards and thus fail by what is now termed buckling.

With only minor differences similar Codes of Practice were established throughout the world during the next two decades, and the host of structures successfully designed in this period bore eloquent testimony to the safety of the procedure. However, there grew up a feeling that the designs were perhaps unnecessarily lavish in their use of steel, and in 1929 the Steel Structures Research Committee was established to inquire into the position. In the course of their investigations a striking result soon emerged, for from tests on actual steel frames it appeared that the conventional bolted connexions between beams and columns were far more rigid than had been supposed. In fact the frames behaved much as

though these connexions were completely rigid. This meant that the bending of a beam would be transmitted through the connexions into the adjacent columns and so into the whole of the frame. The cardinal assumption of the simple design method, that each beam was effectively isolated from the remainder of the frame, was thus seen to be incorrect.

At one fell swoop the carefully erected edifice of the simple design method was thus demolished, although fortunately the buildings which had been constructed on this basis were not similarly affected. In attempting to develop a logical design method the Steel Structures Research Committee was faced with the difficulty that the action of a load on a beam depends not only on the properties of the beam itself but also on the properties of all the other members of the frame. Thus in commencing a design, if attention is focused on one particular beam, its size cannot be determined without knowing the sizes of all the other members, which are as yet unknown. The only way of breaking into this circle is to determine the most unfavourable combination of circumstances as far as a particular beam is concerned by analysing a number of extreme cases of loading and the arrangement of members. Safe rules for the design of beams can then be formulated by assuming the worst conditions to apply to every beam, but there is an inevitable sacrifice of economy. Proceeding in this way the Committee evolved a rational design method for both the beams and the columns, but because of the need for conservatism at each step their method led to only small economies of steel as compared with the simple design method. There was thus little incentive for its use, and the work was almost completely ignored by structural engineers.

This outcome of the Committee's work was disappointing, and at first it seemed that further investigations would be pointless. However, at this time the technique of welding was developing rapidly, and in a welded frame the joints between beams and columns are completely rigid. It was thus evident that a welded frame must possess considerably more strength than the hypothetical type of frame assumed in the simple design method, and that the proper exploitation of this strength would lead to considerable economies. A new approach was called for, and fortunately there were certain indications from recent research in Germany that a rigid frame might be analysed by entirely new methods which could prove to be the key to a simple yet completely rational design method. To understand why this is so it is necessary to digress for a moment to consider the fundamental properties of structural steel.

If a straight steel beam is bent by a load which is not too great, it is found that when the load is removed the beam behaves elastically by springing back to its initially straight configuration. When a beam is bent elastically the deflexions produced are directly proportional to the applied load, an observation first made by Robert Hooke in 1678. Because of its mathematical simplicity Hooke's Law has almost invariably been assumed as the starting-point in structural theory for over two centuries. However, the first concern of the structural engineer is often to guard against a complete failure of his design, and so it is relevant to inquire what happens when a steel beam is loaded up to the point of failure. If the load on a beam is increased steadily, it is found that at a certain value of the load the beam quite suddenly begins to bend far more than hitherto, and when the load is removed there is only a small elastic springing back. The major portion of this large amount of bending is then seen to be localized at the most heavily loaded point of the beam, where there is the appearance of a hingeing action. The permanent

deformation which is observed when the load is removed is due to what is termed plastic flow of the metal, and the beam behaves as though it remains elastic until a plastic hinge forms at the most heavily loaded section. When the plastic hinge rotates the deflexions of the beam become so large that it would certainly cease to inspire any confidence in its ability to carry more load, so that although it does not break it effectively fails.

Thus before failure can occur in a simple beam the central portion passes out of the realms of Hooke's Law into a condition of plastic flow. In the case of a rigid steel frame, failure will not usually occur at the development of the first plastic hinge, for the formation of several hinges is required before excessive deflexions can develop. Thus it is evident that methods of structural analysis based on Hooke's Law cannot furnish estimates of collapse loads, but only of the loads above which plastic behaviour commences.

The simple design method and the alternative proposed by the Steel Structures Research Committee were both based on elastic analysis, Hooke's Law being assumed for each component of the frame. It was therefore necessary to assume in these methods that the structure would become unsafe if plastic flow occurred anywhere, for the analysis could not be extended beyond this point. For a rigid steel frame this assumption is far from the truth, and collapse will often be delayed until the load is as much as 50 per cent. greater than the load at which plastic flow first occurs. This means that no elastic design procedure can possibly produce the most economical structure, for the reserve of strength which is available during the change from the formation of a single plastic hinge to the development of enough hinges to cause collapse cannot be used.

Soon after the conclusion of the Steel Structures

Research Committee's work, Professor J. F. Baker, who had played a prominent part in the investigations, initiated research into the problem of developing a design method based on plastic analysis for the determination of collapse loads, first at the University of Bristol and later at Cambridge. The work was interrupted by the war, but sufficient knowledge had been gained to enable the Morrison indoor table type of air-raid shelter to be designed. In this design the plastic hinge behaviour of steel beams was used to absorb the energy developed by the collapse of a building up to three storeys in height upon the table.

The post-war years saw the development of direct methods for calculating the collapse loads of frames. Despite the fact that Hooke's Law, with all its attractive mathematical simplicity, had to be discarded, the plastic methods of analysis proved to be far more simple than the elastic methods. They are based on the assumption that none of the columns will fail by buckling, and for this assumption to be valid it is necessary to know the conditions governing buckling in columns which have entered the plastic range. These conditions are not yet fully understood, and for this reason the plastic design method is at the present time limited in its application to the simpler types of steel frame. When properly applied it results in the saving of as much as 30 per cent. of the steelwork, but although its use has been permitted in Britain since 1948 the response of the structural industry has been disappointing. However, it is hard to criticize a profession in which safety is rightly regarded as of paramount importance, and when a design method, though fallaciously conceived, has stood the test of time it is not surprising that a new method, even though it has been rigorously proved by experiment, is regarded with some suspicion.

Whereas the steel-framed building is of recent origin,

the art of bridge building goes back some thousands of years. The first durable bridges were of masonry arch construction, and the Etruscans in Central Italy developed the semi-circular arch form, which was taken over by the Romans and brought to a high degree of perfection. Of the Roman arches the Pont du Gard aqueduct, which rises over 160 feet above the level of the river bed, is perhaps the most famous. Another great Roman work is the Alcantara bridge over the river Tagus in Spain, with main arch spans of nearly 100 feet, which was built by Caius Julius Lacer for the Emperor Trajan. The bridge stands to this day, so justifying the proud builder's declaration 'Pontem Perpetui Mansuram in Saecula Mundi'. In 1812 the French destroyed one of the two main spans in the face of the Duke of Wellington's army. This span was subsequently repaired in the native granite stone, and although the Romans had used no mortar whatsoever in the construction the restorers were compelled to point their joints. There is no record of how these arches were designed, but the Romans must have possessed satisfactory rules of thumb which enabled safe structures to be built.

In medieval times there was little or no bridge construction, and the Roman methods were forgotten, but the Middle Ages saw the revival of arch building, a notable example being Old London Bridge. This bridge was begun by Peter of Colechurch in 1176 and completed thirty-three years later, and it survived for over six hundred years. At about this time the famous Pont d'Avignon was built by St. Bénézet. This bridge originally consisted of thirty arches with a total length of over half a mile, but only four arches now remain. A later bridge was the Ponte Vecchio over the river Arno in Florence, built in 1367 and lined with goldsmiths' shops, which still stands today.

Arch construction flourished during the Renaissance, and design rules based on accumulated experience were formulated. Thus Alberti, in his 'De re aedificatoria' of 1485, gave such empirical rules as 'the width of the piers should be one quarter of the height of the bridge', and 'the thickness of the arch stones should be not less than one-tenth of the span'. An elegant bridge constructed at this time was the Santa Trinitata Bridge in Florence, with three spans of about 90 feet each, which was destroyed by the Germans in the Second World War. A remarkable proposal to span the Golden Horn with a 900 feet masonry arch was made by Leonardo da Vinci, and although this bridge was never built its design has recently been examined and stated to be sound.

In the eighteenth century some important advances were made, principally in France, where the Corps des Ingénieurs des Ponts et Chaussées was formed in 1720 as a central authority for approving all plans for bridges and other works in central France. A feeling grew up that the laws of statical equilibrium could be applied to structural problems with advantage, and several manuals were published in which this approach was adopted, the first being produced by Bélidor in 1729. In this manual the theory of arch design proposed by Lahire was put forward; this theory, while incorrect, was at least a reasoned attempt to derive a design method founded on the all-important laws of statics. Indeed, it is hard to see how the conditions of statical equilibrium can fail to enter into any scientific method of structural analysis or design, and Lahire's work, differing in this respect from the empiricism of the Renaissance, thus represented a significant advance.

A further important step forward was taken in 1747 when the École des Ponts et Chaussées was formed, for this was the first institution in the world to present

organized technical courses. The first director was Perronet, a famous bridge designer who based his designs on Lahire's theory, and we may conjecture that through his influence a scientific approach to design was taught. However, he failed to recognize the importance of a memoir published in 1773 by Coulomb, more famous for his researches in electricity and magnetism, in which an improved theory of arches was given, and this work passed unnoticed for forty years. This is all the more surprising in view of the fact that Coulomb was himself a member of the Corps des Ingénieurs.

Towards the end of the eighteenth century the era of modern bridge construction was ushered in when the first iron bridge was built, this being the 100 feet span arch over the river Severn at Coalbrookdale, completed in 1779 and still in service today. A considerable number of bridges of this type were built in England during the next forty years. During this period the suspension bridge also came into use in both Great Britain and the United States, the most notable of these bridges being Telford's chain suspension bridge over the Menai Straits with a span of 580 feet, which was completed in 1826. Telford was a man of no scientific training who possessed an intuitive grasp of the fundamentals of structural theory and the strength of materials amounting almost to genius. It was said of him that he 'had a singular distaste for mathematical studies, and never even made himself acquainted with the elements of geometry; so remarkable indeed was this peculiarity, that when we had occasion to recommend to him a young neophyte in his office, and founded our recommendation on his having distinguished himself in mathematics, he did not hesitate to say that he considered such acquirements as rather disqualifying than fitting him for the situation'. But in a project of the magnitude of the Menai Bridge even Telford was not prepared to be guided solely by instinct, and he carried out loading tests on the actual suspension chains.

We now encounter the figure of Navier, who was undoubtedly the founder of modern structural analysis. Navier graduated from the École des Ponts et Chaussées in 1808, and soon returned there as a member of the teaching staff, becoming a professor in 1821. In developing his courses of lectures, he set himself the task of bringing together the scattered scientific knowledge in the field of structural engineering and presenting a systematic development of the subject. The necessity of filling the many gaps in existing knowledge which he thus encountered led him to solve many important basic problems.

Navier's method of approach differed fundamentally from that of his predecessors. In the field of arch theory, for instance, we have seen how Lahire introduced the all important conditions of statical equilibrium. The remainder of his analysis, however, was based on somewhat erroneous notions of how an arch would fail. Navier, in considering the problem of a metallic arch rib, hinged at its ends to rigid abutments, saw that the laws of statics alone were insufficient to determine the important horizontal forces at the abutments. Instead of deriving the additional conditions needed for the solution of the problem by considering the state of the arch at failure, Navier assumed correctly that the arch rib under normal working loads would behave elastically, thus obeying Hooke's Law. This assumption, coupled with the condition that the abutments cannot spread apart, enables the problem to be solved. Thus if we imagine that under load the ends of such an arch rib are perfectly free to slide horizontally, there can be no horizontal force at either abutment and each end of the arch will move horizontally. Having assumed Hooke's

Law, Navier was able to calculate the amount of this movement, which we shall suppose to be two inches at each end. On the same assumption he was able to calculate the inward movement caused by a one ton horizontal abutment thrust, which we shall suppose to be one inch at either end. Then by simple proportions he was able to deduce the value of the horizontal abutment thrust which would exactly cancel the spread due to the loads; with the figures assumed this thrust would be two tons. Once the horizontal abutment thrust is determined, all the forces in the arch rib are known, thus defining the state of stress throughout the rib.

This coupling of Hooke's Law and the geometry of distortions with the laws of statical equilibrium constitutes the central core of all elastic methods of structural analysis, which have dominated the field for over a century and are only now being slowly supplemented by other methods such as the plastic methods which I have described for steel frames. Navier was the first to state this procedure in a systematic form, and he went a step further in proposing that the results of elastic analyses should be compared with existing successful structures so as to deduce safe stress values, which could then be used in the formulation of rational design methods based on elastic analysis.

When the French Government became interested in the possibility of constructing suspension bridges, Navier was sent to study the developments in England in 1821 and again in 1823. In a Memoir which appeared soon after, he gave the first published theoretical analysis of suspension bridges, and this paper remained a classic for the next fifty years. We may conjecture that during his visits Navier's attention had been drawn also to the cast-iron arches which had then been constructed, for the theory of metal arch ribs which has already been referred to appeared only three years later when he published his lectures as the famous 'Résumé des Leçons'. Here in all probability is an early example of important theoretical work inspired by practical constructions.

Most of the early suspension bridges were unsatisfactory in that they were too flexible, like their primitive forerunners. This resulted in excessive vibrations being set up due to wind or the passage of moving loads. Many failures occurred due to these causes; a 449 feet span bridge over the Tweed at Berwick was blown down six months after completion in 1820, and in 1831 the Broughton suspension bridge failed owing to oscillations set up by troops marching in step. The first suspension bridge designed to carry railway traffic was completed in 1830. It was to carry the Stockton and Darlington Railway over the Tees, but the passage of trains caused large vertical waves to run along the deck, and its life was very brief. The larger bridges were less prone to these troubles, owing to their greater weight in comparison with the loads, but even the Menai bridge had its deck repeatedly damaged by storms. However, it survived until 1940, when it was completely reconstructed.

It was evident that to carry railway traffic successfully the deck of a suspension bridge would have to be extremely stiff. Realization of this need led Robert Stephenson to a unique development in bridge building. In order to carry the Chester and Holyhead Railway over the Menai Straits a bridge of large span was required. His original plan was to use suspension chains to carry a rectangular wrought-iron tube through which the traffic would pass, the tube thus forming a very stiff monolithic deck. The design was based on tests carried out by William Fairbairn on a 75 feet long model tube, but after the towers had been built up to the height required for the suspension chains it was decided on the basis of the test

results to dispense with the chains, thus converting the bridge into a girder type. The fine appearance of the Britannia Bridge which results from the high towers is thus accidental. This bridge, with its two centre spans of 460 feet, was completed in 1850, and is still in use today.

Fairbairn's tests revealed some unforeseen difficulties, for the plates on the upper surface, which worked in compression, failed at a lower load than was anticipated by wrinkling into small wavelike formations. This phenomenon was a more complex case of buckling, and was encountered because the plates were thin in relation to their width; the difficulty was overcome in the final design by replacing the upper plates by a cellular structure. Somewhat similar difficulties were experienced with the side plates, which required additional stiffening members. The form of buckling thus revealed for the first time was the object of an extensive investigation by Hodgkinson, who had been called in by Stephenson and Fairbairn to interpret the test results, and who in 1847 became the first Professor of Engineering at University College, London.

The advent of railways brought about a tremendous upsurge of activity in the field of bridge construction. In England the early railway bridges were principally metal and masonry arches, the suspension bridges having proved to be too flexible, but in the United States another form of construction came into use. For reasons of economy and the lack of other suitable materials close at hand timber was used extensively, and this lent itself readily to the truss type of construction, in which a framework is built up by connecting together a number of long and comparatively slender members at their ends. Some trusses of this kind had been built by Palladio at the time of the Renaissance, and several of the early American railway bridges followed this pattern. Gradually iron came to be used for some of the truss members, and in 1840 the first all metal truss was built by Whipple. Up to this time little theory had been employed in truss design, and it was Whipple who first developed a systematic method for determining the forces in truss members for certain simple types of truss. The trusses which Whipple discussed were characterized by the fact that they just possessed enough bars to be able to sustain load; Palladio's truss is in this category, for the removal of any one bar would cause the truss to collapse under any loading. Such trusses are called statically determinate, for the forces in all the members can be found from the laws of statical equilibrium alone.

Apart from Whipple's analysis, which though correct was unnecessarily long, the problem of truss analysis did not receive immediate attention by scientists. Eventually Clerk Maxwell, celebrated for his development of the electromagnetic theory of light, published a paper on truss analysis in 1864 which described the systematic procedure for obtaining the forces in a statically determinate truss which is used today. In addition Maxwell gave details of the elastic analysis of a truss which contains more bars than a statically determinate truss, his method following the classic pattern of Navier's work. Unfortunately Maxwell's paper was presented in an abstract form, without any accompanying figures, and it passed unnoticed by engineers until ten years later, when Otto Mohr rediscovered Maxwell's theorems and brought them into prominence. The Maxwell–Mohr method is based essentially on the Principle of Virtual Work, and a rival method was produced soon afterwards by Castigliano which has been termed the method of Least Work. All structural engineers appreciate the misleading character of these indolent-sounding descriptions, and yet one of the most important techniques recently developed has been termed the Relaxation Method.

It is now generally accepted that steel arches are more suitable than suspension bridges for long span railway bridges because of their greater rigidity, and so the completion of the St. Louis rail and road bridge in 1874, consisting of three main arch ribs with spans of over 500 feet, marked an important practical advance. In this bridge the arch ribs themselves consist of two parallel tubes connected with diagonal bracing. Each arch was built out simultaneously from both piers to meet in the middle, the half-arches being tied back during erection by cables passing over temporary towers on the piers. The deflexions under the self-weight of the half-arches could not be computed accurately, for the ribs were effectively curved trusses and the Maxwell–Mohr method of analysis was not known at the time. A loan of half a million dollars depended on the closing of the first arch by 19 September 1873, and when this operation was first attempted with only four days to spare it was found that the gap was 2¼ inches too small to receive the last member. It was thus necessary to contract the erected steelwork, and 60 tons of ice were packed round the ribs before the closing member could be inserted.

It is interesting to recall that precisely the opposite trouble was experienced in the closure of one span of the Forth Bridge in 1886. In this case the steelwork was packed with wood shavings and cotton waste soaked in naphtha which when lit caused a sufficient expansion to allow the completion of the last joint.

Since the time of the St. Louis arch several longer span arches have been built, but similar troubles have not been encountered owing to the use of the Maxwell–Mohr theory to allow for the deflexions. The Hell Gate arch over the East River in New York, completed in 1916 with a span of 977 feet, is notable for being the most heavily loaded major bridge in the world. It also served as a prototype for the Sydney Harbour Bridge of 1,650 feet span, which was completed in 1932. These long span arches were also erected by building out simultaneously from each side, the members being lifted into place by a crane which crept out along the erected portions. In the Sydney Harbour bridge the cranes weighed 600 tons, and the half-arches weighed 14,000 tons, and the deflexions due to the cranes and self-weight were allowed for in ensuring that the two half-arches would meet at the crown, enabling the final connexion to be made.

We have seen how the early suspension bridges were mainly unsuccessful owing to their lack of stiffness, and how Stephenson conceived the notion of the stiffened deck but abandoned the suspension chains in his tubular bridge. It was left to William Tiernay Clark to erect the first prototype of the modern type of suspension bridge with a stiffened deck. This was the 666 feet span bridge over the Danube at Budapest, completed in 1849, in which the railings at each side of the roadway were securely fastened to the deck system, thus rendering the bridge more rigid in respect of vertical movements. In later designs a separate stiffening truss was provided; thus in 1855 John Roebling successfully completed the 820 feet Grand Trunk suspension bridge over the Niagara river below the falls, which was provided with an 18 feet deep stiffening truss. This bridge carried both road and rail traffic successfully for over forty years, but was eventually replaced by an arch to carry the increased volume of rail traffic. The great potentialities of the suspension bridge were soon after realized in the Brooklyn bridge over the East River in New York. Begun by Roebling in 1867, and completed by his son sixteen years later, this bridge spans 1,595 feet, and originally carried two street-car and two elevated railway lines, as well as two lines of road traffic.

The provision of stiffening trusses transformed the analysis of suspension bridges into an extremely complicated statically indeterminate problem, which soon received attention. Thus in 1860 Rankine, who was Professor of Engineering at Glasgow, published the first approximate analysis of the action of stiffening trusses. Rankine was primarily a mechanical engineer, and his first published paper bore the intriguing title 'An experimental enquiry into the advantage of cylindrical wheels on railways'. Rankine's theory of stiffening trusses was later improved upon by several investigators, and in 1888 Melan outlined the so-called 'deflexion theory' containing the essential ingredients of the modern analysis which was used in the design of the large suspension bridges in the United States.

Owing to its rapid expansion and geographical situation, New York City was a fertile field for bridge construction, and in 1903 the Williamsburg bridge of 1,600 feet span was completed. The deflexion theory was not used in its design, and the stiffening truss is 40 feet deep; in contrast the Manhattan bridge of 1,470 feet span, completed six years later, was designed by this theory and has a stiffening truss only 24 feet deep. Both of these bridges spanned the East River; the navigable Hudson River on the other side of Manhattan Island is much wider and so presented an outstanding challenge. This was met when the George Washington bridge with a span of 3,500 feet was completed in 1931. This bridge is so massive that the provision of a stiffening truss was considered to be unnecessary, but although the bridge has since proved to be perfectly stable we shall see that later events suggest that the designer was somewhat fortunate.

The span of the George Washington bridge did not remain the largest in the world for long, for the Golden Gate bridge at San Francisco was completed in 1937 with a span of 4,200 feet. This bridge is more slender than the George Washington, and was provided with a stiffening truss of 25 feet depth, but even so in 1938 and again in 1941 a 60 m.p.h. gale caused a series of 2 feet ripples to run along the deck. Then in 1951, in a 69 m.p.h. gale, vertical ripples of 11 feet were measured in the deck, which was swinging 12 feet from side to side. No irreparable damage was done on this occasion.

The successful completion of these giant bridges strengthened the view that all the problems relating to the design of suspension bridges had been solved, but then came a remarkable disaster. In 1940 a 2,800 feet suspension bridge over the Tacoma Narrows in the State of Washington was completed. Although designed to resist 120 m.p.h. gales, this bridge behaved in the most lively fashion in very moderate winds, the deck swaying from side to side while vertical ripples ran along it. In its exuberance the bridge would show off its parlour tricks under breezes of only 6 to 8 m.p.h., and drivers complained that cars ahead of them kept disappearing temporarily from sight amongst the billows. Then only four months after its completion, in a 42 m.p.h. wind, the oscillations built up to an unprecedented extent, and the whole deck broke loose and crashed into the river. After this disaster an investigation was immediately commenced, and the cause soon became apparent. The deck of the bridge had been stiffened by a solid girder, so that the wind forces were much greater than they would have been if a latticed truss had been used. These forces had been allowed for in the design, but in addition the deck was made to resemble an aeroplane wing section, although admittedly not a very streamlined shape. Thus any slight tilt of the deck would produce a vertical force analogous to the lift on a wing, and in addition other forces would be brought into play tending to rotate the

deck still further. These forces would be opposed by the natural tendency of the deck to spring back to its original position, so that a small oscillation would be set up. This oscillation would result in whirling vortices of air being thrown off the deck alternately from the top and bottom, and these vortices in thrusting back against the deck would stimulate the oscillation still further.

Since these wind forces resulting from some small initial disturbance would themselves be small, it is by no means easy to see how the oscillations could have built up to such a disastrous extent. The explanation lies in the fact that large oscillations can be built up by the application of a succession of small impulses if these impulses are correctly timed. We instinctively do this when pushing a child on a swing, the essential point being that the frequency with which we apply the pushes is exactly the same as the natural frequency with which the swing oscillates when left to itself. Each push then feeds more energy into the system, so that a large swinging motion can be built up from a long enough succession of even the smallest impulses. Something of this kind occurred in the Tacoma bridge at a wind velocity of 42 m.p.h., the frequency of the vortex impulses then coinciding with the natural frequency of the bridge structure.

As a result of this failure new designs of suspension bridges are prepared with the possibility of the establishment of oscillations in mind, and it is comforting to know that a model of the proposed 3,300 feet Severn bridge has been thoroughly tested in a wind tunnel at the National Physical Laboratory. The vital problem of the determination of the natural frequency of a suspension bridge, which is clearly of considerable difficulty for such an intricate system, has also been solved.

This brief survey of advances in bridge construction has shown how each engineering development has given rise to new and fundamental scientific problems. The theoretical advances have in turn been used by engineers in designing more ambitious bridges, although in the early days there was often a considerable delay in this process. As I have already remarked, structural engineers are naturally conservative, for theirs is a profession in which safety is of prime importance. For this reason there was often in the past a considerable reluctance to use novel theoretical treatments, which led to lighter structures, when a cruder design method had at least proved itself in practice. But nowadays the picture has changed, and bridge designers are more than willing to effect even minor improvements in their design techniques. The reason for this change of outlook is not hard to seek. Each large bridge is characterized by the fact that nearly all of the load which it is called upon to carry is the weight of the bridge itself. Thus the centre span of the George Washington bridge comprises upwards of 100,000 tons of steel, which is about eight times as much as the useful load of traffic which it can carry. Any improvements in design which result in a decrease in the required sizes of the members or cables thus brings about a reduction in the major portion of the loading, which in turn enables further economies to be made in the steelwork. The inducement to use refined methods of calculation is thus enormous, and indeed if crude methods were employed it is probable that the bridge would be unable to support its own weight and so would fail owing to what has been aptly termed its 'superabundant ponderosity'.

Even in the smaller bridges self-weight can be an important item, and so the trend towards further precision of design methods has been inevitable. In contrast, the weight of steelwork in the average steel-framed building

is but a small fraction of the total load which it sustains, so that design improvements do not lead to the same progressive economies. It is doubtless for this reason that there has not been the same eagerness to make use of such developments as the plastic theory. It must also be recalled that the present lack of a design method for columns precludes the universal application of the new theory. Nevertheless, the plastic methods should be used wherever possible in the interests of the national economy, for otherwise steel, which is one of Britain's most valuable products, will not be employed to the fullest advantage.

It is fitting to conclude by inquiring whether the universities can make any positive contribution towards ensuring the most rapid use of the results of applied scientific research. One obvious approach to this problem is the establishment of post-graduate courses, in which industrial designers can be acquainted with the results of research which has recently advanced to a point at which it can be of practical use. This scheme has been tried out at several universities, but the response has been discouraging, because the men who would derive the most benefit from such courses are the very men whom firms are most reluctant to part with, even for a short time. It is therefore all the more important that those who are engaged in applied scientific research should take every opportunity of meeting industrial designers on their own ground, for such encounters will not only often suggest new fundamental problems for study, but will also provoke discussions of the possible applications of recent research.

These suggestions refer to the present situation, but it is of perhaps greater interest to look to the future. Our present-day undergraduates will in the course of time assume positions of responsibility in industry, and we must endeavour to shape their minds so that they will then be receptive to new developments. This demands that much of the teaching should be concentrated on the fundamentals of each subject, for a thorough knowledge of basic principles is essential for the understanding of any new advances. But a mere presentation of these principles would stultify the critical faculty, and it is also of great importance to develop the necessary flexibility of outlook. This can be done by examining the way in which these principles are applied in a few cases to actual design procedures, and to encourage reasoned discussions of the assumptions which are made. A course of study of this kind, resting on a firm foundation of scientific principles and leading also to an intelligent grasp of their applications and limitations, should not only produce the required depth of vision in the future engineer but is also in full accordance with the tradition of our University.

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GREAT BRITAIN
AT THE
UNIVERSITY PRESS
OXFORD
BY
CHARLES BATEY
PRINTER
TO THE
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