MINUTES OF PROCEEDINGS.

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Walter Shellshear, President, in the Chair.

THE METALLIC ARCH.

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THE able address which Mr. Benjamin Baker delivered about six months ago as president of the mechanical section of the British Association should have the effect of concentrating the attention of engineers on some startling facts, the reality or existence of which had hitherto been almost completely ignored, but the importance of which it would be difficult to exaggerate; for they are associated with unmistakable indications of approaching contingencies that may lead to the most serious catastrophes, unless stringent precautionary means be adopted for their prevention. The facts alluded to are, as many of you will have perceived, those pertaining to the deterioration in quality of either iron or steel which recent experiments have conclusively proved will ultimately arise from the frequent application of even a comparatively light stress.

In 1849 Nasymth remarked that the alternate strain in axles rendered them weak and brittle. The royal commissioners who were appointed during the year 1849 for the purpose of instituting inquiries as to the suitability of iron for railway works and appliances, stated in their report that "iron bars scarcely bear the reiterated application of one-third the breaking weight without injury, hence the prudence of always making beams capable of bearing six times the greatest weight that could come upon them." Again, about ten years subsequently, Mr. Fairbairn and Professor Unwin carried out an extensive series of experiments on a 20ft. wrought iron girder which furnished confirmatory evidence as to the correctness of the results arrived at by former investigators; and, as Mr. Baker remarked, "once more the same important but disregarded facts were forced on the attention of engineers." The interesting and comprehensive experiments of Wohler supply additional grounds for our contracting an incredulity as regards the wisdom that guided the Board of Trade authorities in framing their rules and regulations, which, it is to be feared, have been too frequently availed of to the fullest extent.

Up to the present the rules adopted by engineers even of recognised ability have been and continue to be most conflicting as regards the greatest intensity of unit stress that ought to be employed for fixing the sectional dimensions of the various component parts of an iron or steel structure. Some of the more timid and cautious members of the profession have acted on the principle of putting plenty of material into their designs, and although this practice can scarcely be regarded as being conducive to economy, it is certainly one that may be pursued with more or less impunity, provided the surplus material be judiciously distributed. Others, on the contrary, have expressed themselves in favour of extending the present legally recognised limits of stress, especially in the case of steel. But, if statistics were available, the author is of opinion that it could be shown that the majority of existing metal structures have been designed so as to barely meet the requirements of the Board of Trade regulations, at least so far as those portions of a structure subject only to tensile stresses are concerned. In framing these rules, no doubt, the Imperial Government officials were influenced by the conviction that in fixing five tons per square inch as the maximum intensity of unit stress which their inspectors would approve of in wrought iron fabrications, they were making provision for a factor of safety of four. But, if recent statements be correct, and so far we have no reason to doubt their accuracy, if it be true that neither wrought iron nor mild steel will support even one-third of their original breaking weight when tested in tension after having been subjected for some years to the reiterated application of comparatively light loads, if this fact be regarded as being satisfactorily established, we are thereby forced to admit the possibility of the more severely strained portions of existing structures not only being worked without the existenee of a safety factor of four, but of even being strained beyond the elastic limit of the material employed – a contingency on the momentous import of which it is unnecessary to dilate in addressing a meeting consisting exclusively of members of this association.

Of course it rarely happens that any part of either a girder or roof is required to withstand the full intensity of stress for which it was intended that provision should be made; still, one is justified in assuming that each of the more severely tried members of such structures will have, at some period or other of its service, to resist this maximum intensity of stress, as it would certainly be false and what might be styled clumsy engineering to base important calculations on impossible or impracticable hypotheses. But even supposing that under the most unfavourable circumstances this maximum intensity of stress were not to be realised, still, if iron and steel became gradually and continually deteriorated in quality from the frequent application of comparatively light or other loads, if these metals under the influence of strain suffer a considerable diminution in the magnitude of their ultimate tensile strength, becoming simultaneously dangerously deficient in ductility, it necessarily follows that each and every one of the existing metallic fabrications which have been designed on the girder principle and which are subject to intermittent loading, will become unequal to the duty of efficiently fulfilling the end for which they were erected, while, perhaps, as in the case of well cared structures, manifesting every semblance of stability, rigidity, and soundness.

Iron and steel fabrications are, as you well know, liable to suffer very considerably from the effects of climate, and the rapidity with which this species of decay takes place is strikingly illustrated by the following remarks, which appeared in a comparatively recent number of *Engineering* :—"The rapid decay experienced by iron bridges which are neglected has recently been exemplified in Callowhill-street bridge in Philadelphia. When lately the painters were set to work on this structure, their preliminary exertions in cleaning off the rust brought off flakes of oxide from $\frac{1}{4}$ inch to $\frac{3}{8}$ inch in thickness. This at once revealed the extent to which the injury had already gone, and called for some attention to the necessity of an immediate survey. The fact that the weakening process had already proceeded to a dangerous extent, was shown by the vibration which was so violent that the men had to hold on when a heavy load passed over, to avoid being shaken from the swinging stages. On examination it was found that not only had rust invaded the material of the girders, but that the whole bridge which is built on a rising grade, had moved down hill so far as to tear out the top course of the upper abutment. The structure was only completed in 1875, and thus ten years of neglect has sufficed to bring it to the verge of destruction."

Although an iron or steel bridge may, in the absence of proper supervision and attention, become totally unfitted to meet the requirements of ordinary traffic after the lapse of a few years, especially if it should occupy a site in close proximity to the ocean, in which position oxidation would be likely to proceed and develop with more than normal rapidity. Still this oxidation or surface disintegration which, if permitted to continue its course unchecked, might be expected to ultimately culminate in the most disastrous results, is nevertheless subservient to the salutary influence of regular inspection and other precautionary expedients. It is an evil that does not exhaust the numerous resources which modern science and modern observation have placed in the hands of the engineer. It is, in fine, a phenomenon that permits of being closely observed, examined, investigated, and accurately gauged as to the extent and character of its development. Not so, however, with its prototype, the internal or physical deterioration of the metals whose properties and peculiarities we have been engaged in considering. This latter is a species of qualitative depreciation that covertly becomes increased, thus developing a treacherous and occluded weakness in what may, nevertheless, be designated a most wonderful material, which, in conjunction with the achievements of mechanical science, has enabled the skilled engineer to wield that almost incommensurable power which has wrought such a thorough and complete revolution in the habits, customs, needs, and predilections of human society.

There is, perhaps, no purpose to which iron has been more extensively applied than the construction of bridges, especially railway bridges; and, so far as the author can ascertain, it has been the practice of wrought iron bridge designers to avoid, as far as possible, the introduction of compressive members into their designs, simply because these members not only require to be of sufficient sectional area to withstand the effects of their respective stresses due to the most unfavourable disposition or arrangement of loading, but because it is also essential for them to be efficiently stiffened in order that they may be capable of discharging their duties as pillars or struts. As the quantity of material which it is usual to appropriate for this stiffening not unfrequently amounts to a considerable percentage of the total weight of a truss itself, it is only reasonable to expect that compression members, particularly long compression members, would be dispensed with whenever it is feasible to do so. If, however, wrought iron, when alternately exposed to a tensile and compressive stress, or even to the reiterated application of a comparatively light tensile stress, becomes brittle and suffers a considerable diminution in the magnitude of its ultimate tensile strength, it is obvious that whatever advantages or superiority it might otherwise be supposed to possess as a material for the formation of tension members in structures subject to a variable intensity of loading, are more than counterbalanced by the existence of this most treacherous quality, which, in conjunction with the effects of oxidation, may possibly, at no distant date, manifest its potency in a startling series of deplorable accidents. It may be that the majority of existing railway bridges are in a highly satisfactory condition, as most probably they are. Some may be in no immediate danger of dismemberment, whereas others, comprising those that have been more severely strained, may be on the verge of destruction, while perhaps displaying every visible indication of soundness, as would occur in the case of structures which had been regularly cleaned and painted. Lest you should be disposed to regard this latter statement as being inconsistent with the teachings of past experience, it may not be inexpedient to quote again from the address of Mr. Baker, who is beyond question a most distinguished authority on everything that pertains to the stability of iron structures. Mr. Baker, in the address already referred to, states that "it is an open secret that nearly all the large railway companies are strengthening their bridges." And again he says, "it had come under my notice as a practical engineer that if the compression members of a structure were unduly weak, the fact became quickly evident, perhaps under the test load, but if, on the other hand the tension members were weak, no evidence might appear of the fact until frequent repetition of stresses during several years had caused them to fracture without any measurable elongation of the metal."

Although we may now consider it as being conclusively established that wrought iron becomes gradually deficient in ductility and tensile strength from the repeated application of comparatively light stresses, it is equally well established that the rapidity with which this qualitative depreciation takes place is far from being proportional to the rate of increase of the average intensity of working unit stress ; and hence it is feasible to considerably prolong the life of a bridge beyond that to which it would otherwise attain by reducing the maximum stress per unit of sectional area which will be permitted to strain its tension members. The adoption of this alternative, however, would necessitate a formidable augmentation in the weight of structures which are already in too many instances cumbrously and unwarrantably heavy, and at best, could only be regarded as supplying a means of staving off the inevitable for a few brief years. On the contrary, so far as the author is aware, it has not been recorded that either wrought iron or mild steel develope any quality under the influence of strain which would render them unsuited to being employed for the compression members of any type of structure, so that a well-constructed bridge strut, if it could be only preserved from the effects of oxidation, should be capable of fulfilling its duty for an almost unlimited length of time.

The foregoing, amongst other considerations, have led the author to the conclusion that the present ungraceful form of main girder is, except for small spans, doomed to an early decline in popularity, and that the iron or steel bridge of the future must be that in which a minimum amount of material shall be subject to tensile stresses of varying intensity, while all members so exposed shall be of minor importance, and shall admit of being replaced with the least amount of delay, inconvenience, and expense. It is, of course, difficult to say exactly what form such a structure may assume, but, so far as the writer is enabled to glean from the faint glimmer of light that may be descried in the dim distance of futurity, it seems highly improbable that any novel form of structure will be conceived capable of affording greater facilities for the fulfilment of the conditions just enumerated than the modern development of the metallic arch, such as those that have been recently erected across the Douro, at Oporto, and across the Adigi, at Verona.

The arch, as you are aware, is of great antiquity, having a most interesting history that loses itself in the twilight of tradition, and, from whatever aspect it may be considered, possesses many peculiar and excellent properties. The grace, symmetry, and beauty of modern stone arches are familiar to every traveller, especially those who have traversed the fertile plains and blooming valleys of the British Isles. The imposing bridge that spans the Dee at Chester, the magnificent stone viaducts which connect the opposite banks of the Thames at London, the celebrated Highland bridges of Telford, and the elegantly wrought granite arches that were a short time ago erected across the Liffey at Dublin, after the designs of Mr. Stoney, are structures that have gained a world-wide reputation for the harmony of their proportions, and for the feelings of admiration with which the contemplation of their manifest stability and eminent adaptability is capable of animating the reflective bystander. As regards the weather-worn arches of olden times, it would certainly be superfluous, if not presumptuous, to dwell at any length on the irresistible fascinations of their mystic charms—to attempt to tread the paths that have been hallowed by the footsteps of so many illustrious artists, so many distinguished essayists, and so many accomplished wooers of the lyric muse.

The metallic arch cannot be said to possess such a variety of æsthetic properties as its prototype, the stone arch, Its appearance is not calculated to foster the development of poetic imagery. Neither is it likely that it will ever be assigned a prominent position in any of the exquisite pastoral scenes that may be evolved from the fertile imaginations of our landscape artists; but, on the contrary, it possesses the inestimable advantage of being by far the most pleasing, and in most instances, the most economical form in which iron or steel may be worked into the now indispensible metallic viaduct. It admits of being erected with the greatest facility, and without centering, across deep ravines, impetuous rivers visited, perhaps, with destructive periodical floods, and in many other cases where a girder bridge could only be constructed at excessive cost, or by unfavorably contending against most formidable difficulties. Owing to its extreme relative lightness it is especially adapted to being employed for large spans, for which any description of girder reaches such cumbrous proportions in comparison to the load to be carried. For example, a pair of wrought iron bowstring girders, of 300 ft. span, designed to carry a single line of railway, would weigh about 360 tons, whereas a pair of wrought iron arch rings if erected under similar circumstances, would not weigh more than about 190 tons, which could, of course, be considerably reduced by substituting steel for iron. Again, rapid strides have been made within recent years towards bringing to a satisfactory state of efficiency some of the processes that have been patented for the protection of iron and steel from the effects of oxidation. After a little time some one or other of these methods will undoubtedly be rendered applicable to structures of any magnitude, and as the metallic arch may be designed so that its principal members shall be exposed only to compressive stresses, thereby being insured from the effects of any qualitative deterioration that may take place, the conclusion naturally suggests itself that the day cannot be far distant when it will be feasible to maintain a well designed iron or steel arch in a desirable condition of preservation for an almost unlimited length of time and without incurring any but an insignificant expenditure for maintenance. No doubt there are instances, perhaps many instances, in which the abutments required for an arch would be found more costly than those which would be sufficient for a corresponding parallel or bowstring girder, but except in particularly unfavorable cases, the great saving in material coupled with its increased durability, which would be realised by adopting the former type of structure, should be capable of more than covering whatever additional expense might be incurred in making provision for the thrust which an arch truss would develop at its springings.

There is, perhaps, no problem liable to engage the attention of an engineer more enveloped in obscurity or more exclusively couched in what is to most individuals perfectly unintelligible phraseology than that which embodies the theory of the modern form of the wrought iron or steel arch truss. Some of the ablest mathematicians of the present generation have focussed their knowledge and ability on the consideration of this most interesting subject, which is daily becoming of greater importance, but they all seem to have been equally unsuccessful in bringing the results of their labours within the reach of those who find it inconvenient to cultivate an extensive and intimate acquaintance with the higher branches of mathematics. Mr. Max Am Ende contributed a very able paper to the 31st vol, of *Engineering*, on his proposed Douro bridge ; and Professor R. H. Smith published three most interesting articles on redundant structures, including the metallic arch, in the 49th vol. of the *Engineer* ; but the investigations of both of these gentlemen have culminated in long and complicated formula, the application of which would involve a rather considerable knowledge of analytical geometry as well as of the integral calculus. Certainly, these latter subjects are of very great interest, and when skilfully manipulated, can be turned to immense advantage in the hands of the accomplished engineer. They have not, however, been so generally studied as their importance demands, whilst those who were zealous enough to acquire a familiarity with them during school or college days have had so little opportunity of utilising their knowledge, that it has in a great many instances lapsed into so unmanageable a condition as to surround the chances of success in dealing with compound integrals and other mathematical matters of a kindred nature with an unpleasant degree of doubt and solicitude Under these circumstances it must be highly desirable that some method should be devised which would enable us to dispense with the higher branches of mathematics when engaged in determining, approximately at least, the stresses in the several members of an open webbed metallic arch or abutting truss, similar to those represented by the diagrams in Figs. 1 and 4.

The determination of stresses in any description of truss which is non-redundant, and which is allowed to move horizontally on its bearings is, under ordinary circumstances, an operation that permits of being performed expeditiously and with almost mathematical precision. But in the case of structures rigidly fixed on their bearings, and which consequently develope an abutment thrust, the task of proportioning the sectional area of each member to the maximum stress it will have to withstand becomes a matter of considerable difficulty, and can only be effected by resorting to one or other of the established tentative methods, none of which are capable of yielding absolutely correct results. For example, if the ends of the truss delineated in Fig. 1 were permitted to move freely on their respective supports, nstead of abutting as represented, only three forces would have to be considered when calculating the stresses produced in the extreme bays by any system of vertical loading, namely, the vertical reaction of either abutment and the stresses in the bays themselves. As these three forces are necessarily in equilibrium when the structure is stable, and as the magnitude of one of them, the vertical reaction may be readily determined from the given distribution of loading, that of each of the remaining two may be ascertained by simply drawing an ordinary triangle of forces according to the method so fully explained in the author's paper on graphic statics, which was read before the members of this association at the March meeting of last year. But, should the structure be erected as shown in the figure, an additional force of an unknown magnitude, namely, the horizontal abutment reaction, is thereby introduced into the foregoing problem, which then becomes indeterminate, *i.e.*, incapable of direct solution ; for, so far as the writer is aware, no means have been devised whereby it is possible to determine the unknown magnitudes of three forces which constitute a portion of an equilibrating system consisting of three or more forces meeting at a point. It is the existence of this horizontal reaction in the case of all bridges or roofs exerting a thrust against their abutments which renders the preparation of designs for such structures both tedious and difficult. In fact, if the magnitude of this reaction were once known, the problem of proportioning the sectional areas of the several members of an abutting truss such as that represented in Fig. 1 would be comparatively simple ; and, it is to be hoped that the method for its determination which is now about to be submitted to your notice, and which is analogous to that adopted by Professor Clark Maxwell in dealing with solid web arch rings hinged at the springings, may commend itself to your favourable consideration.

As the term "Modulus of Elasticity" frequently enters into any discussion connected with the determination of stresses in all structures capable of exerting an abutment thrust, it may be well for us, before proceeding further, to direct our attention towards acquiring an accurate perception of its meaning.

It has been ascertained that, within certain limits, the extension of a bar of iron is practically proportional to the intensity of unit stress producing that extension or elongation. Thus, if any bar of iron be extended a certain amount under some particular tensile stress per square inch of sectional area, that extension will become doubled, trebled, &c., according as the stress producing it is doubled, trebled, &c., and, from the existence of this proportionality it necessarily follows that, no matter how many different tensile stresses may be applied to that bar, the ratio obtained from dividing the total elongation by the corresponding stress per square inch of sectional area would be found to possess exactly the same numerical value for each particular unit stress. What is true of the extension of the whole bar must also hold good with respect to the elongation of each particular part of it. Hence, we may say that the elongation of an inch in length of any bar of iron divided by its stress per square inch of sectional area gives a ratio which, within certain limits, is practically of an invariable or constant value, and the numerical value of this constant ratio is termed the "modulus of elasticity" of that class of iron from the behaviour of a specimen of which this constant ratio has been deduced. The different qualities of iron, as well as the greater number of materials used in the construction of engineering and architectural works, have their corresponding moduli of elasticity, which may be found tabulated in Dr. Stoney's book on the theory of stresses, and also in other text books treating of the principles of construction.

Let l be the length (expressed in inches) of a bar of any material whose extensions are subservient to the law of elasticity just referred to ; l' its total elongation (also expressed in inches) when exposed to a total tensile stress S (expressed in tons) ; a, its sectional area (expressed in square inches) ; and E, its modulus of elasticity (expressed in tons per square inch). Therefore $\frac{l'}{l}$ expresses the elongation of one lineal inch of the bar under a tensile stress per square inch of sectional area, which may be expressed by the ratio $\frac{S}{a}$; and consequently, according to the definition just given.

$$E = \frac{l'}{l} \div \frac{S}{a} = \frac{a \times l'}{S \times l}$$

or

$$l' = \frac{S \times l}{a \times E}$$

Since it is generally assumed that the modulus of elasticity is the same for compression and extension, it follows that the above formula is applicable not only in the case of materials being subjected to the effects of a tensile stress, but also when these materials are exposed to a compressive stress. Hence, assuming that S denotes either a tensile or compressive stress,

$$l' = \frac{S \times l}{a \times E} \qquad (1)$$

in which l' will represent an extension or a compression according as the material is exposed to a tensile or compressive stress, consequently formula 1 enables us to calculate either the elongation or compression of any member of a bridge, for instance, when the length of that member, its sectional area, the magnitude and quality of the stress to which it is exposed, and the modulus of elasticity of the material employed are known quantities.

Determination of Horizontal Thrust.

Figure 1 represents an abutting truss hinged at its springings and supporting a load uniformly distributed per foot run of span. In this figure, as well as in figure 4, each letter (excepting W, v, and h) denotes a space, and each member of the truss diagram is designated by the two adjacent letters. The uniformly distributed load is, for the purposes of calculation, assumed to be concentrated at the points where the diagonals intersect in the outer flange; and, as these concentrated loads or weights W_1, W_2, W_3, etc., will produce corresponding abutment thrusts from the magnitudes of which that of the total thrust may be derived, it is proposed to deal with each of these weights, commencing with W_2, as acting separately and independently.

In figures 1 and 4 (plate 14) the entire space underneath the lower flange is denoted by the letter Z.