Mr. G. H. PHIPPS said, he had examined this bridge several times during its progress, and he considered the workmanship was the finest he had ever seen. The finish was more like joiners' work than ordinary boiler-plate construction. Although the merits of nearly every variety of girder had been canvassed in the Institution, he hoped it would not be deemed out of place, or hypercritical, to draw attention to some minutiæ of the construction of this bridge. The form of the upper member of the main girder might be compared to an inverted trough, but having, besides the external sides, two other longitudinal plates dividing the trough into three parts. The top of the trough was of considerable substance, but towards the ends of the girder, the external sides were each 2 feet deep and $\frac{3}{4}$ of an inch thick. The pins by which the diagonals were attached to the top of the girder, at intervals of 11 feet from centre to centre, and along the line of which the pressure was propagated from the ends to the middle, were, he thought, too low down; being, in effect, about 8 inches below the centre of gravity of the section of the trough. Wherever the object was to communicate pressure to any material acting in the nature of a column, it was important to carry that pressure along the line of the centre of gravity of the section; for if this precaution were neglected, flexure must take place. In the Newark Dyke bridge,[1] the upper, or compressed member, was made of cast iron, the strain being carried, as it ought always to be, through the axis of the column. Referring, now, to the Charing Cross Bridge, the sectional area of the iron at the middle of the second bay from the end of the girder was not so great, of course, as at the middle of the girder; but the pressure brought on there by the diagonals was greater in proportion than it was in the middle. If his calculations were correct, it would appear, supposing all the iron in the section to be compressed, square on, to the extent of 3 tons per square inch, that that pressure was increased, by flexure, to about 7 tons per square inch on the outside fibres at the lower edge of the trough. There was no point in the construction to which more attention ought to be paid, than this agreement of the line of strain with the neutral axis of the column; and where the intervals between the points of application of the compressing force were considerable, in the present case as much as 11 feet, in which there was room for the column to bend, the matter was very important. In the Britannia Bridge, where the area of the upper member was very great, the pressure was brought on by rivets every 4 inches, and though these were attached quite at the bottom, the radius of flexure could never be greater than that due

[1] *Vide* Minutes of Proceedings Inst. C.E., vol. xii., pp. 601–611, for "A Description of the Newark Dyke Bridge, on the Great Northern Railway," by J. Cubitt.

to the whole deflection of the bridge. The case was very different where the pressure was brought on at wide intervals, and the wider these were, so much the more would be the importance of confining it to the axial line of the material. He would like to hear the opinions of other Engineers on this question, inasmuch as if he were correct in his assumption, that the strain might thus be increased from 3 tons up to 7 tons on the square inch, on any of the fibres of the material, it was evidently a consideration that could not be safely neglected.

Mr. HEMANS said, he regarded this bridge as one of the most perfect pieces of ironwork of the kind ever produced. The great duty each individual cylinder had to perform, from their being so wide apart, and the great load they had to sustain, under the severe tests applied, showed that the work had been admirably put together. There was one part of the structure, however, which seemed to admit of criticism;—that was, the mode of suspending the cross girders, by stirrup-irons, which he thought was not usual; nor did he observe, in the Paper, that the sectional area of the rivets attaching the stirrup-irons to the bottom girders was stated. As a matter of taste, the appearance of the structure would have been improved, if the bottom line of the bridge had been continuous, and the ends of the cross-girders had not been shown. Though there might be a difficulty in making a continuous line, in consequence of the projection for the formation of the footway, still means might be devised for uniting the ends of these girders, so as to present a continuous line. That mode of construction had been adopted in the little bridge over the ornamental water in the St. James's Park; but he thought the effect in that case was not good. He could not agree in the views which had been expressed, as to the position of the pins relative to the top and bottom webs, causing so much greater pressure; because the ultimate thrust and strain must come upon the top and bottom webs, and could not be taken as confined entirely to the line of the pins.

Mr. J. M. HEPPEL said, it has been truly stated, that no universal rule could be laid down for the adoption, under all circumstances, of either continuous or non-continuous girders. In India he had used the continuous girder, not only for the sake of economy of materials, but also for convenience of construction; because the effect of that plan was to save the necessity for providing staging, or scaffolding. The girders were constructed in continuous spans of two lengths each, so that each girder had three bearings,—one in the centre and two at the ends. These double-span girders were put together at one end of the bridge, and were then hauled over to their bearings on the piers. The rivers in India being subject to heavy periodical floods, the erection of staging was a difficult matter, and the plan alluded to had been found to be very advantageous. He imagined, in the present instance, with girders of such magnitude it might be attended with more difficulty. In the cases he referred to, the spans of the girders did not exceed 70 feet, or 80 feet. With regard to the observations of Mr. Phipps, he should have thought the deviation of thrust from the centre of resistance of the upper member, which might be considered in the nature of a column, was calculated to act prejudicially upon it; at the same time it was but fair to presume, that the designer of the bridge had kept that point in view, and would be able to show, that it had been designed throughout on the best principles.

Mr. JOHN COCHRANE said, it was a matter of some difficulty to give a verbal description of the drilling-machine, because, though simple in its action and effective, it was rather complicated in its parts. In consequence of the great number of plates in the top and bottom flanges, Mr. Hawkshaw decided, in order to secure accurate work, that the rivet-holes should be drilled, and not be punched out. For that purpose a machine was designed, which was capable of drilling all the holes through one series of plates, simultaneously, as it would have been too costly to have drilled each hole separately. The result was, that the cost of drilling was less than that of punching; and the cost of three of these machines was covered by the saving of labour which they effected. The main girders had a camber of 4 inches in the middle. This was not obtained in the ordinary way, by variation in the lengths of the diagonals, but by drilling the holes in the plates of the top flange with a pitch of 4 inches, and in the bottom with a pitch of 3·995 inches. Of course great mechanical accuracy was necessary to secure so small a variation, but when the girders were erected, the camber was perfect.

Mr. F. J. BRAMWELL remarked, that they owed a great deal to the President for having decided that the holes should be drilled, and to Messrs. Cochrane for designing the machinery which made it practicable in a commercial point of view. Nothing could be more barbarous than punching the holes. It was a process that destroyed the iron; it was, generally speaking, inaccurate; and it rendered uncertain what portion of the iron carried the strain. It could not be too generally known, that good workmanship was always the cheapest.

Mr. J. SCOTT RUSSELL, V.P., said, that before seeing this bridge, he had been in favour of that more simple process which approached nearer to ship-building and to ordinary girder-building; but the workmanship of this structure appeared to be more of the nature of fitted and finished engine work, and therefore likely to be on the whole more costly, than a simple lattice, or girder bridge. It did not, however, appear, from the actual prices given, which he hoped had been satisfactory to the contractors, that the cost of the bridge was greater than that of a lattice, or a girder bridge; while the workmanship was, in accuracy and precision, greatly superior to anything usually met with in such structures. The success of the plan for drilling rivet-holes had certainly been complete. The general design and organization of the work had enabled this accuracy to be attained; but unless a bridge was systematically designed, so as to admit of the easy application of this system, it might turn out to be dear and unsatisfactory. He should like to hear the reasons which had caused the principle of continuity in the girders not to be adopted to the full extent. He had so high a sense of the value of continuity, that unless the local difficulties were considerable, and the special advantages of an opposite course were very strong indeed, he should in all cases make such a bridge as this continuous. So far as he understood Mr. Phipps' remarks, he agreed with them in principle, he could not say in measure, because he had not made the necessary calculations. He quite felt that the pins which terminated the parallelogram were a great way from that part of the upper web which did sustain the strain, and that before the strain was conveyed to a sufficient quantity of that section, the pins themselves would undergo a strain nearly double that which the top of the girders would ultimately have to sustain as a mean of the whole. No doubt there was some explanation for that, and he only repeated his impression of the correctness of that statement, in order to elicit from Mr. Hawkshaw a full narration of all the circumstances. Possibly it might be said, that the parallelograms, as constructed, took off so much of the strain, that there remained only a comparatively small strain between point and point.

Mr. E. A. COWPER observed that if, as he imagined was the case, in the last bay there was a thick joint to receive the last pin; and that bay was stiffened, to a considerable extent, with plate, so that instead of the line of thrust being horizontal it might with safety be slightly inclined, there could be no objection to the construction. He should be glad to know how the proof weight of 400 tons, for one bay of 154 feet, had been arrived at. It was an excellent proof weight for a girder supporting two lines of rails, as it amounted to nearly $1\frac{1}{3}$ ton per lineal foot on each line, and locomotives frequently weighed 1 ton per lineal foot, or even a little more. He thought all bridges ought to have ample strength to carry a crowd of people; and the public had a right to be informed, what proof weight was adopted, by the Government Inspectors, for proving common road bridges, such as those at Westminster and at Lambeth. He had tried the weight of a number of labourers, by weighing each man individually, and then by measuring the exact space they occupied when standing close together, as in a crowd, when he found their collective weight was fully 140 lbs. per square foot; therefore in designing bridges of large and small spans, he had taken 140 lbs. per square foot as the possible load. He was, however, aware that from 60 lbs. to 80 lbs. was often taken as a test load, but that was far below the weight of a crowd of able-bodied men.

Mr. R. MALLET remarked that, during the building of Buckingham Palace, Mr. Nash ascertained the greatest possible load of human beings that could be brought upon a given space, with reference to the so-called fire-proof floors of the Palace. Within a hoop, he thought of about 20 feet diameter, as many men were caused to stand as could be wedged into it, the last men being lowered down amongst the others. The result gave a load of 120 lbs. per square foot. The particulars of that experiment would be found in the blue-book relative to the floors of that Palace.

Mr. HAYTER stated, that 70 lbs. per square foot was probably the maximum living load that could be crowded on a given space. It was not important to determine this with accuracy, as regarded the Charing Cross Bridge, inasmuch as the side footpaths were the only public thoroughfares across it, and the load on these would be insignificant, when compared with the load that could come on the bridge, if the four lines of railway carried by it were weighted. He might, however, mention, that Messrs. Cochrane and Co. had tried an experiment, selecting for it the tallest and most muscular men in their establishment, and the result proved that the above estimate of 70 lbs. was ample.

In answer to the inquiry as to the amount of strain on the rivets by which the angle-irons carrying the cross girders were attached to the main girders, and also the amount of the strain on the rivets uniting the cross girders to these angle-irons, he would remark that this—which would be a direct shearing strain—would amount to about 3 tons per square inch. This would be the case, assuming a moving load of heavy locomotive engines packed closely together on the four lines of railway, and the footpaths simultaneously crowded with people—an excessive assumption, inasmuch as it was inconceivable that such an occurrence could ever happen by mere accident.

Mr. F. W. SHEILDS said that, with respect to placing the pins in the centre of the section of the top flange, all his experience convinced him, that such a construction, however plausible, was not calculated to obtain the best results from the iron. He believed that the greater part of the section should be at the top of the flange, where the strain was most severe, as in dealing with iron the object was to prevent the commencement of fracture. It was sufficient, therefore, in all such cases, to provide that the pin which attached the diagonal brace to the flange should have sufficient section of flange underneath it to prevent the pin from tearing away from the flange; and if that were done, the pin might be trusted with safety to distribute the compression along the length of the flange. It appeared that the amount of pressure, 8 tons per square foot, upon the clay bottom in the cylinders, was somewhat unusual. In his own practice, unless the clay was indurated so as to approach the nature of shale, he should hardly think of exceeding 4 or 5 tons per square foot. No doubt the results of the severe tests which had been applied to the Charing Cross Bridge were the best proof of its solidity. With regard to the workmanship of the girders, he could also bear his testimony, that he never saw so accurate and well-finished a piece of work of the kind.

Mr. HAWKSHAW,—President,—said, the weight that could be put upon London clay would depend upon the point where the weight was placed. All geologists knew, that if London clay was penetrated to a sufficient depth, it was capable of carrying a very great weight, much more, in fact, than he had put upon it, although the clay near its surface could not generally be loaded to that extent. With regard to the observations of Mr. Phipps, he agreed that it was desirable the pins should be, as nearly as possible, in the line of the centre of gravity, but practically, in all plate girders, it was difficult to do so. In the case of the Charing Cross Bridge, there must be room for the pins, which were 8 inches in diameter, and for the upper portion of the diagonal bars, which were large forgings. Care was taken to provide sufficient strength in the web, through which the pins passed, to avoid mischief.

With reference to the loading of the cylinders, the first two were tested with 700 tons each, and the others with 400 tons each; the greater load was not continued, as it was a tedious, and rather dangerous, process to build up a solid cube of rails 22 feet square, upon cylinders 10 feet diameter, before any stays were attached to them; and it required careful balancing to make the experiment. In applying the load of 700 tons upon the cylinders, as it was necessary to prevent the weight bearing on the castings, spruce deal planks, 3 inches in thickness, and having together a diameter of rather less than 9 feet, were laid upon the top of the brickwork in the cylinder. The upper surface of these planks was about 2 inches above the edge of the cylinders, and on this surface a thin stratum of cement, nowhere exceeding 1 inch in thickness, was carefully laid, to receive first flat-bottomed iron rails, and then other rails laid crossways, and so on, until the cube of 22 feet was built up. When the rails were taken off, there was not the slightest crack in the cement, and the spruce deals looked as if they had not carried any weight. He was surprised to find so thin a layer of cement, placed on an irregular surface of wood, carrying so great a weight, without a trace of the work it had performed. He gave up the continuity in the construction of the girders with some reluctance. At one time it was thought that the girders might be constructed singly, and be lifted into their places. Then, in order to carry out the system of drilling, instead of punching, the plates, he was desirous of simplifying the plates as much as possible. The whole bridge consisted of a repetition of a few forms; two sizes of plates, with a given number of holes in each, being all that was required for a large portion of the structure. By means of the ingenious machine designed by Messrs. Cochrane, for drilling the plates, much better and stronger work had been obtained. The drilling was executed with very remarkable accuracy. He saw plates of the same description piled one upon another for a height of 6 feet, and the accuracy of the drilling was such, that on putting the finger into the holes, or looking down them, they appeared nearly as smooth as the inside of a gun-barrel.

As to the appearance of the ends of the suspended cross girders being objectionable, when the footway was completed that defect would be removed, as the ends would then be hidden from view. He had been found fault with for assuming so much as 80 lbs. per square foot, as the weight of a crowd of human beings. French engineers, and others, were said to be content with 50 lbs. to 60 lbs. per square foot: but he was satisfied with 80 lbs. per square foot,—not that it had much to do with his calculation, because the test on this bridge would be chiefly locomotives. He was bound to say that the work had been executed by Messrs. Cochrane in a very accurate and creditable manner.

Mr. J. Scott Russell, V.P., remarked that in the bow and string bridge erected over the new street at Southwark, for the Charing Cross Railway, the top and bottom members were similar to those of the parallel girder bridge over the Thames at Hungerford; but in the former case the points of support of the diagonals were even farther away from the centre of gravity of the cross section at the top, than in the Charing Cross Bridge; so that the defect pointed out by Mr. Phipps, if it really was a defect, was carried to a greater extent in that structure. However, in the bow and string bridge, the uprights and the diagonals had much less to do; indeed, from the ends being filled up solid, he thought the Engineer intended that the work should be done by the top and the bottom members, the diagonals merely keeping the truss in shape. If that were so, no doubt the construction was right; and in this case, with proper proportions, the work would undoubtedly be duly performed. Now, in the case of the Charing Cross Bridge, the top and the bottom members each consisted of a three-sided box, one of the three sides of each being composed of a large mass of plates, the uprights and the diagonals being at a considerable distance from the centre of gravity of the cross section of the top and bottom members, and the truss being filled up solid at both ends. Therefore, what had, in his opinion, to be determined, was the share of the work which the uprights and the diagonals took. If these were expected to bear a great part of the burden of the work, then he could agree with Mr. Phipps, that the points were too far removed from the centre of gravity of the top and bottom webs, and therefore from their work, and that a heavy strain would come upon them. If, on the contrary, the top and bottom were so firmly fastened, as in this case, that they might be depended upon to do the major part of the work, then the diagonals and the uprights were mere stays to keep the truss in form, and the evil likely to arise from the displacement, so to speak, of the centres of action, was not great; and Mr. Sheilds would, under such circumstances, be perfectly right in saying, that the points of attachment should be kept from interrupting the continuity of the top member, and that it would be preferable to cut the flanges at some distance from the centre of gravity of the cross section, than in any way to interfere with their continuity.

Mr. Phipps thought the question he had raised was of sufficient importance to justify a closer examination; especially as the opinion seemed to be entertained by some Members, that although his theory might be correct, yet very little effect would be produced upon the bridge from the cause referred to. For the sake of brevity, his remarks would be limited to the upper, or compressed, member of the girder, although it was obvious that similar reasoning would apply equally well to the lower, or extended, member. The effect on the former, however, was well understood to be the more detrimental of the two. The calculations applied to the upper part of the girder, in the second bay from the end, at A B, Fig. 1, page 536. With a distributed load of 700 tons on one girder, including the weight of the girder itself, the pressure on the upper member in the first bay would be 175 tons, and in the second bay 475 tons, leaving 300 tons of pressure to be brought on to the intervening pin by means of the diagonals. It was not easy to determine at what height above the centre of the pin this pressure of 175 tons was transmitted from the first bay to the second; but he had assumed it as being very near to the top part of the compressed member, which he had reason to believe was not far from correct. With these data, the resultant of the pressure at A, of 175 tons, and at B, of 300 tons, was 475 tons at C, Fig. 2, a point situated 3·6 inches below the line of the centre

Fig I.

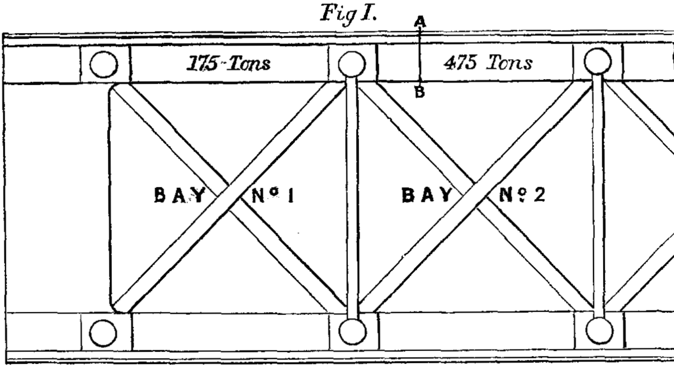


Fig. 3.

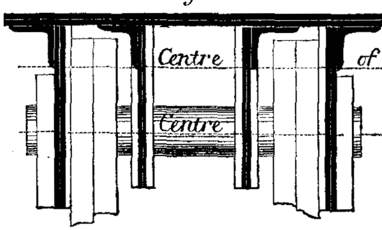


Fig. 2.

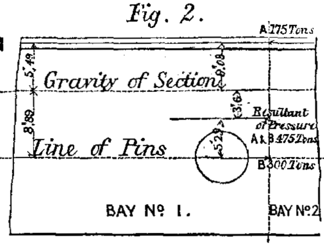


Fig. 4.

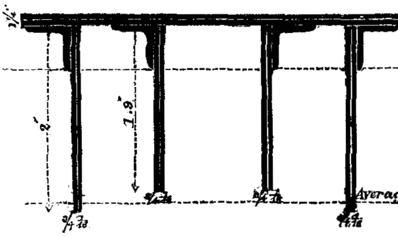
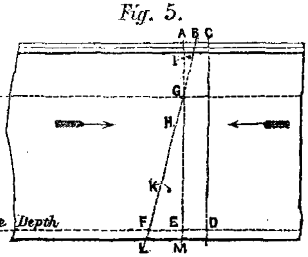


Fig. 5.



of gravity of the section. Fig. 5 exhibited the manner in which this force of 475 tons operated to produce detrimental pressure on the outer fibre of the iron at M. The method of ascertaining this had occurred to him two years ago, when studying the strains upon iron arches, in cases where the curve of equilibrium had travelled away from the line of the centre of gravity. It depended upon this axiom, that whenever a prism of any elastic material was compressed by a force on some line not corresponding with its centre of gravity, flexure must take place, and that to such an extent as would remove the centre of resistance from its original situation until it was perpendicular beneath the force applied. Now, the force of compression on the prism, when applied over the centre of gravity of section G, Fig. 5, might be represented by the content of the solid intercepted between two parallel planes A E and C D. If the compressive force be removed from G to H, in the line of the arrows, the flexure which would ensue might be represented by a certain amount of angular motion of the plane A G M, around the centre of gravity G. By a property of the centre of gravity, any angular movement around G would generate solids of equal magnitude, G A B and G E F, on contrary sides of the centre, and these represented equal forces. Now if I, and K, were the centres of gravity of these solids, then, in order that the point H should become the centre of gravity of the solid F B C D, the solid A C D E into G H must be equal to $(GAB \times GI) + (GEF \times GK)$. When this condition was fulfilled flexure would cease, and H would be the true centre of resistance directly opposed to the compressive force. If E D be laid down from any scale of equal parts, as equal to the pressure in tons on the square inch, then L M would represent the additional pressure brought on the outside fibre of the iron, on account of the flexure, and A B would represent the diminution of pressure on the uppermost fibre.

Applying this to the Charing Cross Bridge, and calling—

$a =$ the area of the whole section of the girder	$= 161{\cdot}25$	square inches.
$b =$ the total pressure . . .	$= 475$	tons.
$c =$ the pressure on the square inch .	$= 2{\cdot}94$	,,
$d =$ the solid A C D E $= a \times c$ . .	$= 475$	,,
$e =$ the solid G A B.		
$f =$ the solid G E F.		
G H	$= 3{\cdot}6$	inches.
I K	$= 16{\cdot}37$	,,
G E $=$ the average depth below G .	$= 17{\cdot}75$	,,
G M $=$ the full depth below G . .	$= 19{\cdot}25$	,,
$t =$ the aggregate thickness of the four vertical plates . .	$= 3{\cdot}25$	,,

$$\text{Then } f = \frac{d \times \text{G H}}{\text{I K}} = \frac{475 \times 3{\cdot}6}{16{\cdot}37} = 104 \cdot 4,$$

and in consequence of G E F being a triangle

$$\text{F E} = \frac{104{\cdot}4}{\text{G E} \times \frac{t}{2}} = \frac{104{\cdot}4}{17{\cdot}75 \times 1{\cdot}62} = 3 \cdot 63.$$

$$\text{L M} = \text{F E} \times 1{\cdot}08 = 3{\cdot}63 \times 1{\cdot}08 = 3 \cdot 92.$$

$$\text{A B} = \frac{\text{L M}}{3 \cdot 2} = \frac{3 \cdot 92}{3 \cdot 2} = 1 \cdot 2.$$

Thus, then, the square on pressure = E D = 2·94 tons on the inch.

The pressure on the bottom fibre = E D + L M = 2·94 + 3·92 = 6·86 tons on the inch.

The pressure on the upper fibre = A C − A B = 2·94 − 1·2 = 1·74 ton on the inch.

Mr. HAWKSHAW,—President,—thought that Mr. Phipps' observations on the Charing Cross Bridge were sound. It was clear that the diagonal strain on that bridge must be transmitted from one pin to another, along the top and bottom members of the bridge; and the nearer those strains passed along the line of the centre of gravity of those members the better. He did not however agree, that in boiler-plate bridges this desideratum was secured by the closeness of the rivets which connected the sides to the top and bottom. He believed the objection applied with more force to many of those bridges than to the Charing Cross Bridge. The girders of the Charing Cross Bridge were so designed, that the diagonal strain at the ends of the girders, if passed from pin to pin, through the vertical webs only, could produce no injurious effect, for the vertical webs at those points were made very strong; and the diagonal strains at the centre of the bridge were so small, that the vertical webs at that point also were stronger than necessary for the mere transmission of the vertical strains. Mr. Scott Russell had, in discussing this point, compared the Charing Cross Bridge with another bridge which was being erected over the new street in Southwark. But that bridge was constructed on totally different principles. It was in fact an arch, and Mr. Phipps' observations could not apply to it. It followed the same laws as any other arch, the weight being merely suspended from, instead of being placed upon, it. The bottom web was substituted for fixed abutments, and it also served to stiffen the roadway and to distribute the load. In that bridge the diagonal braces might be taken away, and still the bridge would stand. They were, however, of use in assisting to distribute the load, and to provide, to some extent, against flexure in the arch. For with loads unequally distributed, all iron arches were subject to flexure. This accounted for the small strain per ton which, it had been observed, was usually placed upon iron arches. If those arches could always be uniformly loaded, the whole would be put in compression; but light malleable and cast-iron arches, with heavy rolling loads, were subject to compression in some parts, and to extension in other parts; and thus it happened that a considerable portion of the cast-iron arches usually erected were not always available in resisting compression, and hence frequently not more than $1\frac{1}{2}$ ton to the square inch, having regard to their whole sectional area, was placed upon them. In some cast-iron bridges subjected to the rolling load of a railway, probably not one-half the section of the rib would be brought into compression.