Correspondence.

Mr. E. ANSON observed that it would be interesting to know the exact proportions of stone grit and cement used in the concrete. In India it was usual to specify these proportions. After fixing the size of stone or ballast to be used, the engineer filled a measured vessel with the stone and ascertained the percentage of voids: he then determined the amount of mortar to be used, making it 25 per cent. more than the voids as measured. The relative quantities of cement and sand or grit to be used in order to make a sufficiently strong mortar were then fixed, and the ratio of all three ingredients was given, taking the quantity of cement as the unit. Thus the concrete used on the work under discussion might be specified as composed of 1 of cement, 2 of sand, and 4 of stone. It was a pity that no borings had been made at the west abutment: this should always be done where arches were to be constructed. It frequently happened that a layer of stiff clay, which appeared to give ample security for a foundation, cracked and collapsed under a moderate weight and spewed up towards the sides when a long drought had occurred, or pumping or drainage operations had sucked the moisture out of the interstices in the clay, or from beneath it. Also, firm sand would sometimes be found to extend only a few feet down, and to rest on a treacherous foundation. If the foundation of the west abutment was on greensand, as the Paper seemed to indicate, the Authors had been quite correct in not carrying the foundation deep, and in spreading the base of the piers and abutments; but even so they would probably have done well to avoid arches altogether on ground which was admittedly soft. On the Assam-Bengal Railway most of the arched culverts had been so badly cracked by the earthquake of 1897 that Mr. Anson had had either to replace them by girder culverts or to strengthen and underpin the abutments and put girders over them. He cited this as an instance of the unsuitability of arched structures on foundations of a doubtful or treacherous nature. It seemed open to question whether it was advisable to use weaker concrete in the foundation than was used in the superstructure. The advisability of allowing the toothing of the cement face-blocks in the arch to relieve the centering of some of the pressure from the mass concrete seemed also to be very questionable, as it would cause stresses to be set up between the face-blocks and the mass Mr. Anson.

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Mr. Anson. concrete before either of them had set properly. However, if the centering had been kept in place, probably no weight had been taken by the toothing and no relief afforded to the centering. A better and more homogeneous result would have been obtained by building the whole arch of concrete blocks. It would have been preferable, also, to make the floor of the diaphragm-wall in the shape of a curved invert, as offering more resistance to any tendency of the original foundations to spew up between the piers. There seemed to be no reason why the cement mortar should have been used in the abutment of the diaphragm-walls. Lime mortar could have been used above water-level with more economy. The "needles or struts" described in the Paper had the appearance of being an afterthought. It would have been better to lengthen the block abutments longitudinally to such an extent as to keep the toe of the slope clear of pier No. 1, or the toe of the slope might have been brought down at 1 to 1, or even steeper, and pitched with rubble. The adoption of these struts, with the doubtful effect of their local thrust against the distributed thrust of the bank, seemed to be a fault in design. It would have been interesting if figures had been given showing the saving effected by the adoption of the concrete-arch design in place of a girder bridge on concrete piers, taking into consideration the difficulty experienced in repairing the arches compared with the facility with which girders would have been jacked up.

Mr. Colson. Mr. C. H. COLSON observed that the advantages of the elliptical arch in lightness might have been obtained, together with the more pleasing appearance of the semicircular arch, by the adoption of the latter with pierced spandrels. It would be interesting if the Authors could state why the load on the foundations had been made so varied; $1\frac{1}{2}$ ton to 3 tons appeared to be a variation for which no adequate explanation was given. Further, had any tests of the bearing-power of the strata been made, and in which material, clay or sand, were the foundations laid? With reference to the use of crushed stone-dust as sand, the following experiments, made by Mr. Colson some years ago, showed that a considerable increase of strength was gained by the use of such dust instead of ordinary sand—at least, when limestone was used—and that, other things being equal, coarser sand made stronger mortar. Each result was the average of thirty-six experiments, the same cement being used for all, and all being tested at the same age. The term "6-to-1" might be applied to very different qualities of concrete, and he would urge that concrete should always be described in terms of the sand, gravel and cement used. If

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Mr. Colson.

Kind of Sand Used.	Sizes of Sand Grains.				
	Passed through 64 Meshes per Square Inch.	Through 64 Meshes stopped on 256 Meshes per Square Inch.	Through 256 Meshes stopped on 625 Meshes per Square Inch.	Through 625 Meshes stopped on 2,500 Meshes per Square Inch.	Through 2,500 Meshes per Square Inch.
	Breaking-Stress.				
	Lbs. per Sq. In.	Lbs. per Sq. In.	Lbs. per Sq. In.	Lbs. per Sq. In.	Lbs. per Sq. In.
Siliceous sand with slight admixture of calcareous . .	146·00	171·95	169·71	146·15	131·39
Calcareous sand of siftings from limestone from stone-breaker	267·63	272·71	240·56	218·98	218·26

water-tight concrete was required, it was necessary that the sand should be rather more than sufficient to fill entirely the interstices of the stone, and that rather more than enough cement should be used to fill the interstices of the sand, and to coat each grain; but as the proportion of the interstices varied so much in different materials, it was difficult, if not impossible, to specify the exact proportions until tests of the materials actually to be used had been made. He had found that the interstices of stone might vary between 50 per cent. in clean hand-broken stone and 34 per cent. in medium-sized shingle, with sand—material which would pass a 100-mesh sieve—removed. The following Table, which was the result of a large number of experiments, showed the amount of mortar which might be produced by different proportions of sand and cement:—

Ratio of Materials.		Quantity of Mortar of Ordinary Consistency produced, in Terms of Percentage Increase or Decrease over the Quantity of Sand used.	
Cement.	Sand.	Increase.	Decrease.
		Per Cent.	Per Cent.
1	½	140·97	..
1	1	47·32	..
1	1½	26·05	..
1	2	15·46	..
1	2½	5·83	..
1	3	3·11	..
1	4	..	8·43
1	5	..	10·76
1	6	..	14·00

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Mr. Colson. Even if proper proportions were used to ensure that all interstices were filled, it must not be expected that thoroughly sound and satisfactory concrete would be produced unless the mixed mass was thoroughly rammed and consolidated in place. As to the question of fine grinding, the following Table showed clearly that the finer the cement the higher was its cementitious value; but the question whether very finely-ground cement could be used must depend on the amount of fine cement it contained and on its price when compared with a coarser cement and its price. It might be cheaper to buy the coarsely-ground cement and use more of it. Each result in the Table was the average of six experi-

Size of Sand Used.	Fineness of Cement Used.			
	As Received.	Screened through 2,500 Meshes per Square Inch.	Screened through 3,600 Meshes per Square Inch.	Screened through 5,800 Meshes per Square Inch.
	Breaking-Stress.			
	Lbs. per Sq. In.	Lbs. per Sq. In.	Lbs. per Sq. In.	Lbs. per Sq. In.
Screened through 2,500 meshes per square inch	122·22	133·70	203·25	240·36

ments. The same weight of cement had been used in each test and the tests had been made at the same age. No mention was made in the Paper as to any preliminary tests for expansion having been made; these, in Mr. Colson's opinion, should always be adopted, preferably by hot-water tests. The method of casings used for the columns was ingenious, but considerable time would have been saved had trussed sides been used and the concrete put in in 6-foot instead of 2-foot lifts. Could any explanation be given as to the use of 2 parts of sand in the test-blocks, and had the quantity of cement been increased in proportion? Also, did the cost given represent the actual cost of the work or merely the price paid to the contractor?

Prof. Gaudard. Professor J. GAUDARD, of Lausanne, considered that the Cannington Viaduct presented several points of special interest; first, in that it was constructed entirely in concrete, with expansion-joints; secondly, in the mode of construction without scaffolding, by means of a cableway for raising and depositing the concrete; and lastly, in the occurrence of an earth-slip during the execution of the work and the remedy adopted. Inverted arches and inclined buttresses of cement concrete for strengthening the feet of piers

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were often employed with success, as in the strengthening buttresses applied to the sides of the foundations of the Pont Neuf[1] at Paris during repairs in 1886–87; or the oblique cylinders of plate-iron and concrete, sunk by pneumatic process, at a bridge over the Schuylkill at Philadelphia, in order to counteract the overturning of an abutment founded upon piles. As, however, the strengthening works in the interior of the third arch appeared to have been employed only as a temporary precaution during the repair of the arch, it would have been better to demolish them subsequently, with the exception of the invert, as having become superfluous and as having a disagreeable effect æsthetically. With regard to the use of the cableway, had not small flying platforms been employed on the piers, around the boxes, to support the workmen? The use of concrete in the construction of tall piers was justifiable only to a certain height —at least if it was considered as being somewhat weaker than masonry in cut stone. In this connection it would be desirable to give some idea of the maximum pressure sustained upon the top of the foundation mass of the base, on the most heavily loaded side, to which the resultant of the forces inclined when one arch only was overloaded. In the construction of arches, concrete, considered simply as a monolithic mass, was particularly liable to cracks and fissures during the movements induced by flexure and by variations of temperature. The Authors also indicated the existence of four expansion-joints in each arch. In the spandrels and the parapets, which had not to act as arches, these joints were modified into slits opening slightly during contraction by cold, and closing again during warm weather. But across the curve of the arch, should not some precaution have been taken to guard against the local crushing of the extreme edges of the intrados and extrados, upon which at times the pressure was concentrated? It might have been done by inserting plates of lead, stopping short at some distance from the edges, as in the articulated arches of the Leibbrand system. In certain bridges this had been carried to the extent of articulating the concrete arch by means of three metallic hinges, for example, in the Munderkingen arch of 50 metres (164 feet), and in the 40-metre (131·2-foot) arches of the La Coulouvrenière bridge at Geneva. The pivoting centre consisted of pieces of steel, working like hinges, placed at the middle of the depth of the joint, and distributing the load over the concrete by the help of stout splayed box- Prof. Gaudard.

[1] *Annales des Ponts et Chaussées*, 7th series, vol. i. (1891) p. 885.

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Prof. Gaudard. bearings of plates and angles. The two semi-arches of concrete, which then acted as simple struts, were slightly swelled out at their middle or at the haunches of the arch, and formed monoliths exempt from all risk of rupture, being free to respond to the effects of temperature. Vertical slits were introduced above the hinges in the walls of the spandrels. String-courses of cut stone were so disposed as to hide these details of construction. The use of concrete, and especially reinforced concrete, in the construction of arches had lately become more general. The effect of temperature-changes upon iron and concrete appeared to be the same from the time that they were perfectly embedded. The Hennebique system[1] had been widely adopted in architecture for beams of small span, and was applied to reservoirs where resistance to extension was necessary; but it had also been adopted for arched bridges and even for straight girders. For this last form, however, with long spans beams entirely of metal were preferable, their calculation being more reliable. In arches, the utility of the metallic reinforcement lay in strengthening the arch-rings against possible flexure. Reinforced concrete in itself formed somewhat costly masonry, but a saving could be effected by adopting a cellular form of construction, and by building bridges not of complete arch-rings, as in stone bridges, but only of isolated members or spaced ribs bound together by a platform also of reinforced concrete. The latter method lent itself particularly to the construction of skew spans built with a series of rings or successive spaced ribs. Thus, Mr. de Crousaz had constructed at Jallieu (Isère) a bridge with a skew-angle of 38 degrees, and having a span of 25 metres (82 feet) on the skew. In the width of 10 metres (32·8 feet) there were six independent ribs, whose intrados was twisted to follow the surface of an oblique cylinder. The bridge at Lausanne, on the road between Chauderon and Montbenon had piers of ordinary masonry, but the six arches of 28·75 metres (94·1 feet) span were executed in reinforced concrete on the system of Professor Melan of Brünn, which had already been adopted to a considerable extent in Austria and in the United States. It consisted in completely embedding in the concrete metallic lattice-work arch-ribs of much lighter construction than would be required for an ordinary metallic bridge, the ribs being braced together only in such manner as to hold them at their correct distances apart during the operation of depositing the concrete around them. The concrete was deposited with normal joints and

[1] Minutes of Proceedings Inst. C.E., vol. cxlix. p. 302.

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was retained laterally by side planking, and on the under side by Prof. Gaudard. the boarding of the centering, which was suspended by adjusting-screws from the ribs themselves, so that the amount of centering properly so-called could be reduced. In making the concrete, 300 kilogrammes of cement per cubic metre (406 lbs. per cubic yard) was mixed with lake ballast and crushed stone from Arvel. This Melan and de Vallière system had been adopted by the town of Lausanne on the advice of experts, and was being carried out under the orders of the engineers Messrs. de Vallière, Simon and Co., and of the architects Messrs. Monod and Laverrière. The employment of iron and concrete in combination clearly required a suitable apportionment of the duties to be performed by the two materials, in such manner that the deformation under compression should be the same for both. The metallic rib started from the pier in the form of a horizontal member 1 metre (3·28 feet) in depth, forming the encastrement, and then it was carried up, following the curve of the arch and decreasing in depth to 0·42 metre (1·38 foot) at the crown (*Figs. 12*). Transversely the viaduct consisted of three zones, the two outer of which were constructed from top to bottom as though they were two separate viaducts having each a width of 5·8 metres (19·02 feet) between the sides, but which were reunited towards the crown by a connecting band 5 metres (16·4 feet) wide, carried by reinforced beams laid transversely on the Hennebique system. The two side viaducts each contained six metallic ribs, of which the two inner ribs were specially strengthened, having to support the central platform over the space between the two viaducts. They were 1·2 metre (3·94 feet) deep at the springing, reduced to 0·68 metre (2·23 feet) at the crown. They were spaced 0·8 metre (2·62 feet) apart, whilst the others were spaced at intervals of 1 metre (3·28 feet). On the outer sides of the bridge the footways were corbelled out for a distance of 0·7 metre (2·29 feet), thus increasing the width of the bridge to a total of 18 metres (69·04 feet). The spandrels were of open construction, in the form of arcades with openings of 1·8 metre (6·9 feet). They were made on the same system except that the metallic rib was solid and was formed of simple curved H section, 0·12 metre (4·72 inches) in depth. It had been assumed that the flexibility of the arches would be sufficient to provide for expansion, but the roadway-platform was provided with a dividing slit on the face of each pier. The highest pier had its foundations carried down to 43 metres (141 feet) below the roadway. Unfortunately, it was to be anticipated that in the course of

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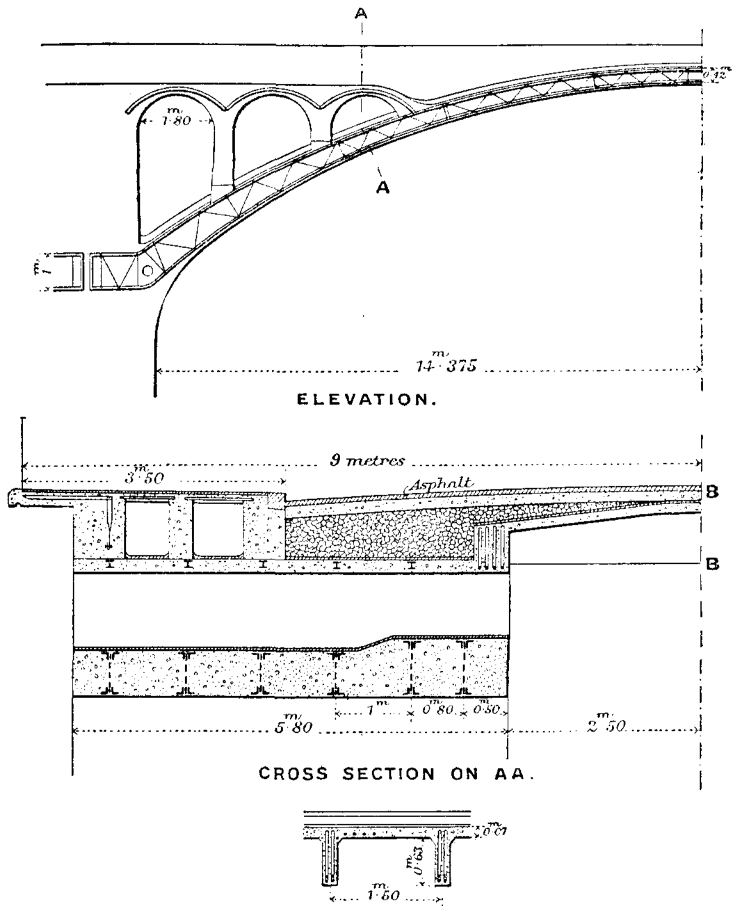
Prof. Gaudard. some years, the filling up of the valley of the River Flon would ultimately bury the lower portion of this work, in the same way as the lower arches of the Pichard Bridge, in the same town, had disappeared. The stone piers had been consolidated

Figs. 12.



LONGITUDINAL SECTION AT BB.

FERRO-CONCRETE BRIDGE AT LAUSANNE.

by a course of masonry in reinforced concrete, which was prolonged through the opening between the two pillars forming one pier. The two higher piers had a second similar course but without this prolongation. The Montbenon abutment had had to

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be subsequently strengthened with rectangular beams of reinforced concrete, in consequence of signs of movement of the earth. From a similar cause, namely, the existence of slipping strata, determined by Professor M. Lugeon, it had been necessary to pull down several foundations, to the extent of 6 metres (19·68 feet) in the base of one of the piers. In the bridge at Lausanne the elliptical form of arch had had to be adopted by reason of the filling up of the valley of the Flon, which would otherwise have risen above the springing; and moreover the metallic reinforcements of that work were better suited to the elliptical form. In France there existed a preference for the full-centered arch wherever it was possible to adopt it, because of the better conditions in that form as regarded the thrust upon the piers in the event of any one of the adjoining arches becoming overloaded; as for example the 25-metre (82-foot) openings of the Crueize viaduct on the Marvejols–Neussargues line, and even the four 50-metre (164-foot) spans of the viaduct of Nogent-sur-Marne. The spandrels were at the same time lightened by internal vaulted spaces. Prof. Gaudard.

Mr. H. HAWGOOD remarked that the Cannington viaduct was an interesting example of the growing use of cement concrete in railway work. At first confined to minor structures and foundations, concrete was now gradually taking the place of steel for spans, wherever conditions permitted its use. In the United States there had been numerous instances during the past 2 years of steel bridgework, put out of service by the increase in the rolling loads, being replaced by arches of plain or reinforced concrete, in addition to its extended use in new work. On the 57 miles of the San Pedro, Los Angeles and Salt Lake Railroad between Los Angeles and Riverside, California, all the masonry was of concrete. The largest and most important structure on the line was the Santa Ana viaduct, over the river of that name near Riverside, built by contract from his plans and under his personal direction as Chief Engineer of the railway; but besides the Santa Ana viaduct there were two arches of 30 feet, and many of smaller span, down to culverts of 4 feet. For openings of less than 4 feet, slab tops were used, thickest at mid-span and sloping gently to a less thickness at the sides; for small water-ways this had been found to be a cheaper and more expeditious mode of construction than arched tops. The following was a brief description of the Santa Ana viaduct:—Its general dimensions were: length, 984 feet, made up of eight main arches, each of 86 feet clear span, an approach arch at each end of 38 feet 6 inches clear span, and abutment retaining-walls. Refuge-bays, 10 feet by $2\frac{1}{2}$ feet, were Mr. Hawgood.

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Mr. Hawgood. provided over each pier for workmen and their tools—an essential provision on long structures carrying fast traffic. The viaduct was of mass concrete throughout, without any metal reinforcement. The total quantity of concrete used was 12,544 cubic yards. Careful levelling failed to show any settlement when the arch-centres were struck. All foundations were carried down to rock, the shallowest foundation in the river-bed being 10 feet, and the deepest 54 feet, below water-line. Fourteen months were occupied in building the structure, and but for difficulties encountered in the foundations of the seventh pier the viaduct could have been completed in 11 months. In preparing the design it was deemed to be absolutely essential, considering the permanency of the material used and the difficulty that would attend any removal, that sufficient strength should be provided to meet any possible increase in the weight of rolling stock and loads. The steel bridgework (longest span 110 feet) used at other points of the line where for lack of headroom arches were not possible, was designed to meet rolling loads of two engines coupled together, each with a concentrated weight of 200,000 lbs. on a driving-wheel base of 15 feet and a total weight of 220,000 lbs. on a 23-foot base, with tenders of 120,000 lbs. on a wheel-base of 16 feet, making for both engines and tenders a weight of 680,000 lbs. on a total base of 109 feet, followed by a train of 4,500 lbs. per lineal foot. The equivalent uniform load between the centre of the arch and the joint of rupture was 6,000 lbs. per lineal foot. With this live load over the whole arch, or over one-half of it, the other half remaining unloaded, the line of resistance was contained within the middle third of the arch-ring (depth of rings at crown 3 feet 6 inches, at springings 4 feet 6 inches), the maximum stress being 290 lbs. per square inch. With the live load increased to 14,000 lbs. per lineal foot, which was considered the limit of possibility, the line of resistance was still within the middle third, the maximum stress becoming 355 lbs. per square inch—a safe figure. The Russo bridge,[1] 72 feet 6 inches in span, on the Southern Railway of Italy, was said to have a stress of 370 lbs. per square inch, and the highway-bridge over the Danube at Munderkingen[2] had a maximum stress of 559 lbs. per square inch. In general, 500 lbs. per square inch appeared to be accepted as permissible. The cost of the structure was slightly less than would have resulted from the use of steel girders on the same foundations. The cement used averaged 1·03 barrel per cubic yard

[1] Minutes of Proceedings Inst. C.E., vol. cliii. p. 362.
[2] *Ibid*, vol. cxix. p. 224.

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Mr. Hawgood. of finished concrete in the arch-rings, and 0·93 barrel per cubic yard in the other parts of the structure. The viaduct was opened for regular traffic on the 12th March, 1904, since which date it had been in continuous service. No settlement or cracks had appeared. The gradients descended to each end of the viaduct, making it naturally a point of high speed. To nullify impact the concrete was overlaid with ballast to the thickness of 3 feet. Heavy trains at 60 miles per hour produced no perceptible jar or tremor. The track was laid with 75-lb. steel rails, with eighteen sleepers, 8 feet by 7 inches by 8 inches, to the 33-foot rail. He hoped the Authors would add to the value of the Paper by giving supplemental information as to the rolling loads for which the Cannington viaduct was designed, and the maximum stress to which the concrete would be subjected, and it would be of great interest to learn the reasons which had governed the adoption of the general design of a series of arches of small span and rise, with light supporting piers (where the failure of any one arch or pier would endanger the entire structure), in place of larger spans with abutment-piers. In the Santa Ana viaduct each pier was an abutment-pier, capable of sustaining by itself the thrust of the arch. The practical value of this arrangement had been clearly brought out during construction, when, owing to the difficulties in founding pier No. 7, arches Nos. 1 to 6 inclusive had been completed, the centering removed, and the work on these six arches all cleaned up, 3 months before pier No. 7 was ready for arches Nos. 7 and 8. According to the following Table, larger

—	Cannington Viaduct.	Santa Ana Viaduct.
Length over all	600 feet	984 feet
Width over spandrels	16 „	17 „
Average height above footings	85 „	72 „
Ratio of contents of circumscribing dimensions	1	1·49
Concrete	6,429 cubic yards	12,554 cubic yards
Arch spans	50 feet	86 feet

spans and heavy piers did not appear to involve more concrete. In proportion to their relative dimensions, the two designs required essentially the same amount, if the probable difference in live loads was taken into consideration. Perhaps the Authors would say, also, whether there were any indications of cracks in the mass concrete, emanating from the right-angled corners of the toothing

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Mr. Hawgood. into the face-blocks of the arch-rings. Would not the chamfering of the internal corners of the long face-blocks to an angle of 45 degrees have been safer? Sharp re-entrant angles in concrete were very apt to produce cracks during setting.

Mr. Kirkpatrick. Mr. C. R. S. KIRKPATRICK asked what conditions had demanded the construction of the viaduct in concrete instead of brickwork in cement. Good facing-bricks were stated to be obtainable at Torrington, 72 miles by rail from Axminster: common bricks were probably made near to Axminster, and at the worst they were made at Yeovil, 21 miles by rail from Axminster. Assuming that facing-bricks would cost 45*s.* per thousand, and common bricks 30*s.* per thousand, at the kilns, he calculated that if built of brickwork in cement the viaduct would have cost £9,943, or 30*s.* 11*d.* per cubic yard, as against 32*s.* 1*d.* for concrete. This estimate made no allowance for a cableway, because with brickwork it would not have been required; but use of all plant was included. For the same price, Torrington bricks might have been replaced by Staffordshire blue bricks. It therefore appeared to him that a brick viaduct would have been slightly cheaper than concrete. It would have had a better appearance, and have been less likely to give trouble in the future; and it seemed that the one redeeming feature of concrete viaducts, namely, considerable saving of expense, was absent in this case.

Mr. Lart. Mr. F. A. LART observed that the application of such a material as concrete to the construction of an important engineering structure, such as a railway-viaduct, was interesting, if only as showing the faith which some engineers were prepared to place in a material which could be of an entirely satisfactory quality and great usefulness, but which had definite limits of utility and disadvantages which might more than outweigh its cheapness, and which was under a natural suspicion of being unreliable and somewhat untried. The quality of the neat cement and the concrete used in the Cannington Viaduct was evidently excellent, as shown by the tensile and crushing tests; but, as the human factor was all-important in the making of concrete, special tests were not always a positive guarantee of the general quality of the material. The total cost, though so much increased by the additional work necessitated by the subsidences at the west end, did not seem excessive: he would like to know how much was due to the extra work in question. The design and construction seemed good enough, but possibly concrete piers with brick arches and superstructure would have been more satisfactory. He would like to know if the expansion-joints were really necessary, and whether after any natural expansion (apart from subsidence of

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Mr. Lart

piers) the joints came back quite true. The figure given for the opening of these expansion-joints ($\frac{1}{2}$ inch), seemed fairly large: was this due to natural expansion or to settlement of the piers? And were these expansion-joints part of the original design, or had they been adopted on account of the subsidence of the piers? The defect of the structure clearly lay in the insecure and inadequate foundations, and it seemed a very unsatisfactory feature that the piers should have settled so much as 4 inches in some cases and 6 inches in others; equal settlement would not have mattered so much. Though this branch of engineering came very little in his way practically, and he had had no opportunity of experimenting, the idea had occurred to him that sandy, peaty, or other moist and loose subsoils might, without removal, be rendered quite suitable and reliable foundations under practically any load, if they were simply rendered solid by the injection of liquid cement grout into their mass. His idea would be to decide, according to the usual considerations, the area of the required foundation, and its depth according to the character of the subsoil. Then at each corner of the area and at regular and sufficient intervals over its whole surface, 2-inch or 3-inch steel pipes would be sunk to the full depth of the foundation desired; these pipes would be closed at the bottom, except for, say, a $\frac{3}{8}$-inch hole; and the sides of the pipes would be similarly perforated with a suitable number of holes all round and at regular intervals for, say, the lowest two-thirds of their depth. Through these pipes, preferably simultaneously, cement grout would be forced under pressure into the porous soil, until it was thoroughly impregnated, which would probably show itself by the oozing of the cement at the surface. That indication, and the thorough saturation of the required foundation-mass, would be properly secured by not perforating the injection-pipes the whole way up. The cement would require to be not more liquid, especially in saturated ground, than would ensure its remaining fluid and flowing properly until the whole cubic contents of the required foundation were completely grouted. There would thus be formed, probably at a small cost, a solid cement-concrete foundation, which, if made deep and extensive enough, should be quite strong enough to carry any reasonable pressure, and quite immovable. He thought that even peat could be so concreted in situ, and the mere size of the concrete foundations would be of little consideration. He did not know if this idea had ever been put into practice, but would like to have the Authors' views upon it. Also he would like to know how this viaduct was standing

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Mr. Lart. whether there was any limit to the speed or weight of trains passing over it, and whether the Board of Trade had had any objection to raise when passing it. It was a pity that a neat and workmanlike design should have been spoiled by failure and patching at the outset.

Mr. Metcalfe. Mr. A. WHARTON METCALFE thought that the Authors would have added considerably to the value and general interest of the Paper, if they had shown in one of the diagrams the position of the line which, in a voussoir arch, would be the locus of the points of application of the resultants of the mutual pressures between the voussoirs by which the arch was sustained: "equilibrated curve of thrusts" was perhaps the most fully descriptive name for it. In the absence of the data necessary to enable the omission to be made good, it was impossible to locate the curve of pressures; but from general inspection of the diagrams, from experience, and from the fact that the arches were elliptical, it was clear that the curve of pressures would not follow the course of the arch for any considerable distance, but would soon pass from the arch into the backing, which thus became the arch—a constant occurrence in the case of elliptical arches, and one which really unsuited them for railways, or indeed any routes of communication traversed by heavy rolling loads, such as traction-engines, etc., or even for heavy permanent loads. The fact that the curve of pressure passed well above the springing into the backing meant that a considerable portion of the arch near the springing was doing no useful duty, but was in fact mischievous, as it was hanging from the portion of the backing which had become the virtual arch and was transmitting the thrust. This useless load was increasing the weight upon the haunches. If that were done purposely—for instance, in order to assist in neutralizing the effect of a heavy rolling load when approaching the crown—then there was a better way of attaining the object. Greater elegance and architectural beauty might be advanced by an architect as an argument in favour of elliptical arches; but with an engineer they were only an excuse; for it was questionable whether the engineer could find beauty in a form of construction possessing palpable defects, which would be avoided in a correctly designed arch. The semicircular arch was confessedly plain; he had never heard its advocates claim any beauty for it, which was perhaps fortunate, as there should be no temptation to resort to a form which no more fulfilled the conditions of the equilibrated arch than did the elliptical form, and which in respect of material was even more wasteful. The facility with which centering for semicircular arches could be designed, made, and put up, had doubtless claimed adherents. In the arches of the Cannington Viaduct

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the ratio of rise to span was rather high, namely, 1 : 3; with equilibrated arches a ratio of 1 : 10 was quite practicable. He had himself made the calculations for, and been engaged upon the design of, viaducts and bridges in which the ratio of rise to span was respectively 1 : 4 and 1 : 8; these bridges had proved in every way satisfactory and looked extremely well in elevation. Of course, such a ratio as 1 : 10 or 1 : 8, demanded good ground and massive, suitably-designed abutments. In the case under discussion this would have been an advantage, because the abutment-piers could have been moved forward and at the same time lengthened, thus doing away with spans Nos. 1 and 10 and the piers adjacent to them; which would have obviated the risk of exposing the piers to thrust from a possible slip of the earth in the banks. In order to avoid moving forward the abutments, the spans might have been lengthened slightly. He thought there were two principal reasons why elliptical and semicircular arches were more frequently met with than those of the correct form. One was that designers had overlooked the fact that there was an intimate relationship between the curve of thrusts, the curve of a suspension-bridge, and the curve of bending-moments for the same span and the same distribution of load. The other was that no convenient means for calculating and plotting the curve of equilibrium in the case of masonry and concrete arches was readily accessible, or even generally known to exist. At the beginning of the nineteenth century Dr. Charles Hutton investigated the conditions of stability of the arch and deduced a formula expressing them. He considered two cases, namely:—(1) Given the outline of the intrados of an arch, to find the form of the extrados or profile of the roadway which would keep the arch in equilibrium, the thickness at the crown and the span being given. This case was of little practical interest, though it was of theoretical value. (2) Given the outline of the extrados or upper surface of the roadway, to find the form of the intrados of the arch under which it would be in equilibrium, given the thickness at the crown of the arch and the span. This was the case which most frequently occurred in engineering practice where railways, roads, or canals were carried by an arch; and it was of great interest. For the case of a horizontal extrados (*Fig. 13*), the equation to the equilibrated curve of thrusts assumed the special form— Mr. Metcalfe.

$$y = h \times \frac{\log_e \dfrac{x + \sqrt{x^2 - a^2}}{a}}{\log_e \dfrac{c + \sqrt{c^2 - a^2}}{a}}$$

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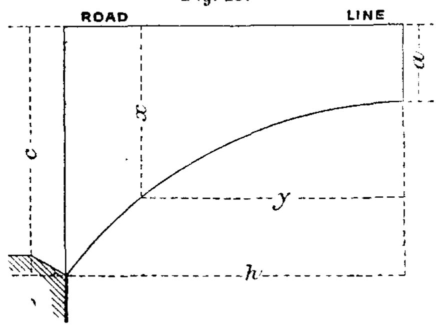
Mr. Metcalfe. where the thickness at the crown = a, the half span = h, and the rise + the thickness at the crown = c; the origin of co-ordinates being the intersection of a vertical line through the middle of the key-stone with the extrados, which in this case was a horizontal line.[1] Calculation was simplified by taking the logarithms of both sides

$$\log y = \log h + \log \log_e \frac{x + \sqrt{x^2 - a^2}}{a} - \log \log_e \frac{c + \sqrt{c^2 - a^2}}{a}.$$

The application of the equation was illustrated by the case of a road-bridge, proposed and designed on this principle by the late Mr. Charles Richardson, M. Inst. C.E., for crossing a railway-cutting

Fig. 13.



near Bristol. The chief particulars of the bridge were: span, 85 feet, built in brickwork; arch in vertical bond, rise 10 feet 6 inches; total thickness at crown 5 feet 6 inches. For this example the constants in the foregoing equations were—

$a =$ 5 feet 6 inches.
$h =$ 42 ,, 6 ,,
$c =$ rise $+ a =$ 10 ,, 6 ,,

and the values of x and y were shown in the following Table, with the radius of the arch at each point:—

x	y	Radius.	x	y	Radius.
Feet.	Feet.	Feet.	Feet.	Feet.	Feet.
5·6	4·68	106	9·0	26·42	74
5·75	7·38	,,	9·8	29·00	,,
6·0	10·40	,,	10·5	31·02	,,
6·5	14·60	,,	12·0	34·29	,,
7·0	17·75	,,	12·75	36·45	55
7·17	18·72	,,	14·0	38·97	,,
8·0	22·61	74	16·0	42·50	,,
9·0	26·42		18·0	45·56	

[1] C. Hutton, "The Principles of Bridges, etc.," 2nd ed., p. 43. London, 1801.

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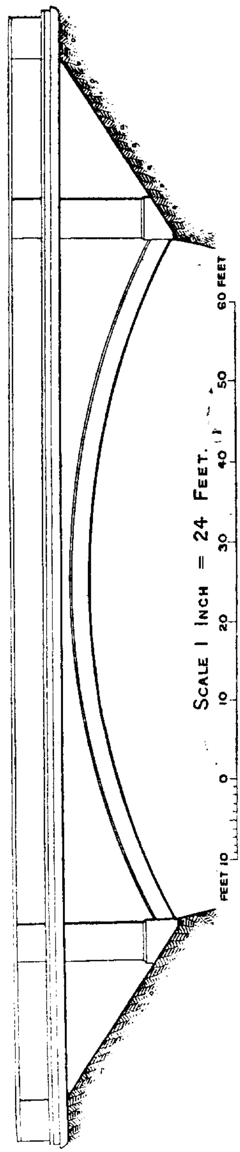
The elevation of the bridge was shown in *Fig. 14*. This bridge would require the arch to be 13 inches thick at the crown, and 15 inches at the springing; and for convenience in building it of brickwork, it would be made 15 inches thick throughout. A 50-ton engine of the common gauge, with a 16-foot wheel-base, would produce a lowering of the crown, when at the centre of the span, of nearly 3 inches, but, as there was a margin of 12 inches thickness to spare, the bridge would be safe under a travelling load of even 100 tons. There was no reason, except the cost of centering, why arches of 400 feet span should not be built of vitrified bricks. With regard to materials, he thought brickwork in cement was a better material than concrete; certainly it was more reliable, and in most cases it would cost less than the amount mentioned by the Authors, though, for the particular case they were dealing with, concrete was doubtless the cheapest material. If arches were built in brickwork, they should be built in vertical bond as shown in *Fig. 15*, and not in rings, which did not unite to form a solid block arch, but had a tendency to separate, the line of thrust passing from one ring into another. Bricks of the highest quality were preferable even to large stone voussoirs, as, being small and handy, they could be swum in the cement mortar and made to take a full-bedded bearing. This it was not easy to do with large voussoirs, which were also liable to be hollow-dressed and to cause the joints to break at the edges owing to the squeezing out of the mortar under pressure. When vertical bond was used for tunnel-work where the radius of the arch was small, the bricks indicated in *Figs. 15* by S_1 and S_2 should be specially-made tapered bricks. They added 4*s*. or 5*s*. per 1,000 to the Mr. Metcalfe.

Fig. 14.



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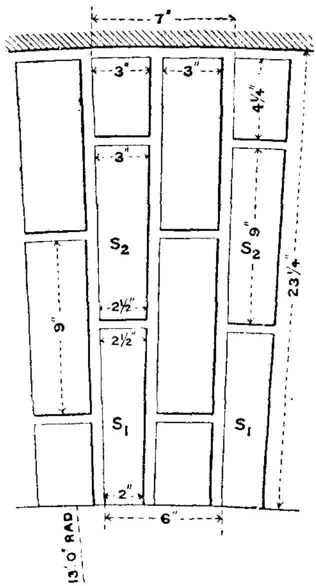
Mr. Metcalfe. cost, but made a better job; and bricklayers soon got to know them and use them without confusion. Vertical bond was of the utmost importance in the invert of a tunnel liable to water-pressure external to the arch, which, if the invert was built in rings, forced them apart. The innermost ring lifted, and it would be followed by each ring in succession if the pressure were sufficient. On an invert built in vertical bond the effect would be to tighten all joints. The building of the invert of the Severn Tunnel in rings instead of in vertical bond, had proved a costly matter, and, in the opinion of the late Mr. Charles Richardson, had been responsible for much of the extra pumping-plant required to relieve the arch and invert from pressure. He thought the expansion-joints were unsuitably disposed, since they divided the arch into three parts instead of the two similar halves which joints at the crown and springings would have given. In the latter case the concrete arch should logically be treated in the same way as a hinged metallic arch, if the joints were thick enough.

Fig. 15.



Mr. Stewart. Mr. Angus M. Stewart observed that until it came to be more generally realized that any arch built with first-class cement mortar was almost as much a monolith as a concrete arch was, engineers would be found to disapprove of the use of concrete in important structures. Some years ago, on opening up a portion of Charing Cross Station on the Glasgow City and District Railway, originally built in tunnel, the greatest difficulty was experienced in breaking up the old brick-in-cement arch. There were no lines of cleavage, and the brick-in-cement had to be quarried into blocks, with the aid of wedges, just as if it had been concrete. This showed that if there was any opening and closing in the joints of a built arch under temperature- or load-stresses, it could take place only where inferior mortar had been used; and, if such movement was considered desirable, lime or other inferior mortar should be used in order to give it free play. A concrete

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arch must be thicker and consequently heavier than a similar arch built with cut stone voussoirs; but in an arch carrying a railway that was a distinct advantage, as the extra weight offered greater resistance to the effects of impact. Concrete was daily demonstrating its superiority over brick and rubble as a material for the construction of arches, and the great economy of using it in place of dressed stone would probably cause it to replace that material in every case where fine architectural effect was not demanded. Mr. Stewart.

Mr. R. F. THORP considered that segmental arches would have been better than the elliptical section used. Besides being easier and cheaper to construct, and more effective, segmental arches were better from an æsthetic point of view when mounted on the lofty piers of a viaduct. The wing-walls should have been extended to prevent the toe of the embankment from reaching the piers. It was always dangerous to allow the loose earth of an embankment to bear against a tall pier, as, in the event of a slip or even settlement of the earth, uneven pressure was brought to bear on the structure which it had not been designed to resist. The extra cost of the longer wings could be minimized by building them with a good batter and by introducing relieving-arches. Comparison between this viaduct and others constructed in masonry and brickwork could be more readily made if the Authors would state exactly the thickness of the arches at the crown and the springing, the section of the piers at the springing, the top of the plinth and the top of the footings, as well as the pressures allowed on the concrete at these points. It would be useful if the Authors would divide the total cost of the viaduct under several sub-headings such as foundations, cement, ballast, plant, centering, labour, and establishment-charges. Mr. Thorp.

Mr. J. WULSTAN TWINBERROW asked for some particulars of the cost of erecting and working the cableway described. It would be interesting to know how much of the 32*s.* 1*d.* per cubic yard, given as the cost of the concrete, was due to its use. A rate of deposition limited to about 30 cubic yards per day suggested that there were not many situations in which cableways could be employed economically. He had on several occasions investigated their use with a view to their adoption in carrying out public works, but hitherto he had always found some more workable alternative. For heavy foundations, such as those of masonry dams, they appeared to be too slow; whilst for deep and narrow tongue or wing trenches he did not think they could be used with safety to the men employed. The surging of the rope must be a great objection in setting heavy masonry when time was any consideration. No doubt there were situations for which they Mr. Twinberrow.

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Mr. Twinberrow. were suited, such as the one described; but he had recently come across several cases in which they had been discarded or supplemented with so much additional plant as to suggest that they might easily have been dispensed with. It was stated in the Paper that the voussoirs were keyed in advance of the mass concrete of the arch, also that the centres settled $2\frac{1}{2}$ inches under the weight of the latter. It would be instructive to know whether the voussoirs had settled with the centres—in which event it was difficult to see how they had relieved the centres of any weight—or whether they had retained their proper position whilst the laggings dropped from them at the crown—when the voussoirs would carry an undue share of the permanent load, and the soffit of the arch would not be flush throughout. Also, an opening of $\frac{1}{2}$ inch in a straight joint through a 50-foot elliptical arch did not seem altogether desirable. In view of this, and of the cost of the structure, he failed to see what advantage had been gained by employing concrete instead of the more usual brickwork.

Mr. Whitley. Mr. H. MICHELL WHITLEY presumed that there must have been some exceptional circumstances to warrant the use of concrete for the Cannington Viaduct, seeing that otherwise, at prices ruling in the South of England, a brick or stone viaduct should have been built for the same or a less sum. Having had experience in constructing large viaducts or clay foundations—and also of some failures—he had found that it was important to give a good rise to the arches; ellipses were graceful but weak at the crown, and where settlement was possible, a semicircle, or a segment with ample rise, was safer. He had also found in building a long viaduct on treacherous ground that it was very desirable to insert abutment-piers at every six or seven arches, and in clay to add a "cut-water," that was, to finish the abutment behind at an angle of 45 degrees, so that if a slip occurred, the pressure of the clay bank was taken off the abutment without injury. It was much safer, however, even if a little more costly, to put in two or three extra arches at each end, so as to reduce the height of the bank to moderate dimensions; and the extra cost was well repaid by the resulting security. The brickwork added between piers Nos. 2 and 3 had spoilt the architectural appearance of the Cannington Viaduct.

Mr. Williams. Mr. G. B. WILLIAMS remarked that the utilization of concrete, either with or without reinforcement, for engineering structures of all kinds, was a question which had so largely engaged the attention of engineers during late years, that it was somewhat surprising to find that this was the first occasion on which a Paper descriptive of a concrete bridge of any kind had been discussed by

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Mr. Williams.

the Institution; though there was in the "Proceedings" a short account[1] of the concrete bridge over the Danube at Munderkingen. Other things being equal, the choice of material for such a structure as the Cannington Viaduct was determined by the cost; and the figures given on p. 10 might therefore have been of greater value, as some guidance to engineers who had to deal with this class of work, if they had been set out in more detail. The amount of £1 12*s.* 1*d.* per cubic yard was the average price for several kinds of concrete, 6-to-1 and 8-to-1, arch blocks and parapet, and also included the staging, centering and cableway, and all the temporary plant used in the construction of the bridge. The price was high, and compared unfavourably with that of the stonework in many masonry viaducts. Probably it was considerably more than the price per cubic yard allowed for this viaduct in the parliamentary estimate. The problem of the distribution of the stresses in a structure of this kind was not easy of exact solution, but supposing the 6-to-1 concrete in the arch, and the 8-to-1 concrete in the haunches, to have been put in simultaneously so as to form a monolith, it would be justifiable to consider the portion of the arch inside the voussoirs as consisting of three large concrete arch-stones, and to draw the line of resistance accordingly. Assuming a moving load of 1½ ton per lineal foot, the maximum intensity of stress appeared to occur near the upper expansion-joint when one half of the span was loaded with the moving load. This stress worked out to about 130 lbs. per square inch, or 8½ tons per square foot, and was considerably below the figure allowed in many other concrete bridges. In the part of England in which the viaduct was situated, there was a very ancient and interesting example of piers being tied by secondary arches underneath, somewhat after the manner described in the Paper, in order to remedy a failure in the original construction. This example, which displayed in a marked degree the engineering ability of the great cathedral-builders of the Middle Ages, was to be found at Wells, in Somerset. The central tower of the cathedral was completed at the commencement of the fourteenth century, and in the year 1338 the piers supporting the great arches underneath it showed signs of such serious failure as to endanger the entire fabric. A second pointed arch was accordingly built underneath each main arch, some distance above the level of the floor, and on this a third inverted arch was added so that its apex rested on the apex of the arch beneath. The result was to brace the four piers together by means of four huge St. Andrew's crosses—an

[1] Minutes of Proceedings Inst. C.E., vol. cxix. p. 224.

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Mr. Williams. appropriate device, seeing that the cathedral was dedicated to St. Andrew. The work was entirely successful, and in artistic effect, at all events, it had much the advantage of the method used at Cannington, where the diaphragm-walls could not have improved the general appearance of the viaduct. It was somewhat surprising to be informed that buff bricks made a good match in point of colour with concrete made with flints. Concrete in any form of construction was always an ugly material, for it was generally very untidy in appearance, and nearly always dried in different colours. Moreover it frequently turned an unpleasant patchy brown or yellow colour in wet weather. For these reasons it was a substance to be avoided as far as possible for viaducts except where the scenery was not such as could easily be spoiled.

The Authors. The AUTHORS, in reply, stated that the extra work caused by the subsidence had cost approximately £1,700. The expansion-joints were part of the original design, and although opinions might differ as to the positions selected for them, they had successfully achieved their object in preventing cracks in the structure, which would undoubtedly have occurred had they not been provided. The portion of the viaduct above the springings could not have remained a monolith 600 feet long. The opening of ½-inch mentioned had occurred in the arch nearest to the east abutment, and was not due to natural expansion but to the pressure of the embankment when first tipped. The joint had closed upon the embankment becoming consolidated. Mr. Lart's proposed method of pumping grout into soft foundations was ingenious, and the Authors thought it would be attended by success in a soft sandy soil. A clayey soil would tend to check the setting of the cement and probably not much hardening of the foundation would result. But it would be a matter for experiment in any given case, an area being selected for treatment and tested by drills before it was decided to apply the method to the foundations of the work. With regard to the form of arch adopted, advantages of the elliptical arch were a saving of material on the haunches and a more graceful appearance. On the other hand, a semicircular arch, not being so flat at the crown, was easier to maintain. The choice was largely a matter of individual taste. In the present instance economy had been the ruling consideration. In turning the arches, the voussoirs and centering had settled equally. The centering, which had been designed by Mr. H. O. Baldry, M. Inst. C.E., would, they considered, be suggestive to anyone who had to carry out a similar work. The total cost of the concrete was made up thus :—

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The Authors.

	£	s.	d.
Labour	4,537	11	0
Use of cableway, stone-crusher and other plant; coal and stores	2,235	9	0
Use of timber and ironwork for shuttering and centering	389	10	7
Portland cement, shingle and sand	2,055	0	0
Office charges	1,097	4	0
Total	£10,314	14	7

The cost of the cableway when erected, complete with masts, winding-engines, second-hand boiler, and shed, had been £1,215. No platforms had been used outside the boxes of the piers, the men, who became accustomed to the increased height as the piers rose, standing either inside the box or on battens placed across the top of it. In view of the movement at the west end of the viaduct, the Board of Trade had required a flagman to be stationed temporarily at the site. The viaduct, the Authors believed, was standing very well.

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20 December, 1904.

Sir GUILFORD L. MOLESWORTH, K.C.I.E., President, in the Chair.

The President.

The President said it was his painful duty to announce to the members the death of Mr. J. Allen McDonald, a well-known member of the Council. Mr. McDonald had rendered valuable service to the Institution, and his loss was deeply felt. The Council had passed the following resolution, which was concurred in by those present:—

"That the Council have learned with deep regret the death of their esteemed colleague Mr. John Allen McDonald, and desire to convey to the members of his family an expression of sympathy with them in their bereavement."

The discussion upon the Paper "On the Construction of a Concrete Railway-Viaduct," by Messrs. Wood-Hill and Pain, occupied the evening.

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