Discussion.

The PRESIDENT moved a vote of thanks to the Author for his Paper. The President.

The AUTHOR exhibited and explained a number of lantern slides illustrative of the condition of the old steelwork of the floor, and of the strengthening operations. The Author.

Mr. T. B. GRIERSON remarked that a very good Paper on the strengthening of Cannon Street Bridge was read at the Institution, describing work which had become necessary on account of the increase in the weight on the driving-wheels of the locomotives. The work described in the present Paper had been undertaken for much the same reason, although there were other reasons also. The underlying cause of all the trouble was the public demand for faster and more elaborate trains, which entailed heavier coaches, heavier engines, and, of course, stronger bridges and permanent way. The Forth bridge was a monument to a Past-President of The Institution, Sir Benjamin Baker, and no less a monument to the contractor, Sir William Arrol. If ever a bridge was designed with the intention that it should require no repairs for many years, it was the Forth bridge. The trouble taken by the Board-of-Trade inspectors to ensure that there should not be a repetition of the Tay bridge disaster would be remembered. Singularly enough, however, the very precautions taken by the Board of Trade inspectors had largely been the cause of the trouble that had been experienced. They were determined that if a derailment took place it should not wreck the main girders, and consequently the engineers decided to make the outer side of each outer trough practically a part of the main girder. As the Author pointed out, had not the weights on the driving-wheels of the locomotives increased by 29 per cent. since the bridge was built, only trifling repairs might have been necessary; but it was evident that the bridge had not been designed for the present loads and speeds. In his view, there were two important lessons to be learned from the Paper. The first was that in great structures like the Forth bridge it was much better to distribute the load on the main girders over a large number of points instead of concentrating it at a few points, as had in fact been done. In 1906, 16 years after the bridge was opened, it was discovered that the transoms were too far apart, or, to put it another way, that the troughs carrying the permanent way were not strong enough. In 1909-10 more Mr. Grierson

Mr. Grierson. transoms were put in, thus shortening the spans of the troughs carrying the permanent way. He could not help thinking that when the bridge was designed the great idea was to have as few supports as possible, so as to give the bridge a better appearance from the æsthetic point of view and also to reduce the area on which the winds, which were very violent in that neighbourhood, could act. The second lesson was that the permanent way should be absolutely free from, and in no way attached to, the main girders. The reason why that had not been done in the case of the Forth bridge was, as he had said, a desire to prevent the possibility of a derailed train running into the main girders. That could be accomplished, however, in future similar bridges in a much easier manner; he would not say a more effective manner, but a cheaper one—which was a very important point at the present time. The new right-angled seating-plate shown in *Figs. 4a* (p. 127) was intended to overcome the difficulty caused by the fracturing of the plates. As the Author said, originally one side of the trough was held rigidly, while the other was flexible. That meant the destruction of the trough sooner or later; and it had happened. He did not wish to say anything which might appear ungracious to the Author, but it seemed to him that the new right-angled seating-plate might not prove entirely satisfactory; before very long further repairs might perhaps be required there, because one half was free and the other half was riveted. The effect on the plate of trains crossing the bridge would be something like that produced by taking a piece of tin and bending it to and fro. The heads of the rivets in the seating-plates were also, he thought, liable to fly off. He wished to emphasize the point that in big viaducts vibration had a very injurious effect, and the trouble caused by vibration had never been so great as at present, owing to the heavy weight of modern locomotives and rolling stock. On the Forth bridge, where there was a signal-cabin at each end, roughly 2 miles apart, he thought a substantial reduction in the speed of trains while crossing the bridge could be arranged: 15 to 20 miles per hour should be ample. He feared that, if that were not done, the severe vibration would cause serious injury to the great main structure. At 20 miles per hour it would only take 6 minutes to cross the bridge, and by thus limiting the speed the vibration would be substantially reduced. The cost of the work described in the Paper amounted to a substantial sum (£147,000). He would like to know how the "cost" had been arrived at, and perhaps the Author also would state what percentage had been added—if that was a fair question. The Institution was greatly indebted to the Author for his excellent Paper.

Mr. CONRAD GRIBBLE asked whether the deterioration of the troughs had not been the subject of rather more inquiry and consideration than appeared from the Paper. An important point was that in the approach spans where, as far as he could gather, the cross girders were 7 feet apart, the longitudinals must have had an ample margin of strength, because there did not appear to be a corresponding increase in strength in the case of those in the internal viaduct, where he noticed the spacing of the cross girders was half as much again. It was significant, therefore, that the longitudinals had had to be renewed completely throughout the viaduct, although at certain parts of it they must have had a very low working-stress, and it was difficult to understand how such a renewal came to be necessary, having regard to the very generous margin of strength. As to the spacing of the cross girders, the Author stated that the general condition of the rail-troughs was better on the central spans than on the approach and internal viaducts, although some of the bearings of the troughs had deteriorated considerably. He gathered that the cross girders were spaced as much as 22 feet 6 inches apart in the central spans, which did not bear out the theory, advanced by the previous speaker, that the cross girders should be more closely spaced, but rather the reverse. The question of the spacing of the cross girders and its effect on the troughs was, he thought, important; but he was not sure that experience gained in the case of a structure like the Forth bridge was a safe guide for general design. It would be interesting, however, if the Author could give further particulars of the ratio of calculated to actual stress, or calculated to actual deflection, obtained in the tests made on the various parts of the structure. He believed that extensive tests had been made of the trough-sections, and possibly very valuable information had been obtained respecting the ratio of calculated to measured stress, which would not only help to clear up the somewhat obscure question why the longitudinals had had to be renewed—even when the cross girders were only 7 feet apart—but would also help in the general question, in which many engineers were interested, of the accuracy of calculations in regard to such members as those under consideration. He gathered they had all been designed, both originally and in the renewal work, as continuous girders, and possibly that fact had been taken into account in renewing and testing them. In the Appendix there was no mention of the span on which the tests were made. It would help in the analysis of the results if that were stated and if further particulars were given with regard to the modulus of the section. There were so many different sections of Mr. Gribble.

Mr. Gribble. channel—four or five of 17 inches by 5 inches, or thereabouts—that it was difficult to gather what the modulus of the section tested was, and therefore no conclusions could be drawn from the Table.

Mr. Brown. Mr. CHARLES J. BROWN thought every one would agree that the planning and execution of the difficult and complicated work described in the Paper reflected the greatest credit on those directly responsible. The conditions had been very onerous, and the work, having had to be carried out, for the most part, during the war, had been thereby greatly complicated; circumstances had been such that the engineer in charge and the contractors must at times have been very hard put to it to carry on. With regard to the original design, it was realized in very early days that the floor would be a source of trouble. Having been associated with the maintenance of the permanent-way part of the structure at that time, he had some knowledge of the bridge, and indirectly he had gained some experience of the conditions met with in regard to the floor. The flexibility of the inner troughs as compared with the stiffness of the outer troughs was no doubt the main source of the trouble. That revealed itself, as the Author stated, by the rivets working loose at the bearings of the troughs on the cross girders, and, further, some of the longitudinal riveting between the bottom horizontal angles and the webs of the troughs also showed signs of weakness. For stretches of several feet, at one place, all the rivets would be loose, showing that the bearing-stresses were undoubtedly too high. Those rivets, of course, had to be cut out from time to time and replaced, and therefore it was anticipated that before very long serious repairs would have to be taken in hand. It was thought at one time that the strengthening the Author mentioned—making good the rivets over the bearings, and putting in short cover-plates at those points—might enable that part of the structure to carry on for a few years longer, but as time went on the trouble proved to be more deep-seated than had been anticipated in the early days, and that led to the resolution to clear the whole thing out, which he thought subsequent experience had shown to be wise. He noticed that the Author gave the increase in engine-weight as 55 per cent. of the weight of the engine in use when the floor was designed. The increase in the total weight of the engine, however, was perhaps a little misleading; the actual figures were equivalent to about 1·90 ton per linear foot as against 1·46 ton, an increase of 30 per cent. That was almost exactly the same as the percentage increase in the axle-load, which was, of course, the important factor for the floor. With regard to the new design, he thought it would be agreed that the designers had hit upon a section which suited admirably the conditions for which it had been designed. Riveting had been reduced to the minimum, and the important point was that there were no rivets between the bearing of the trough and the cross girder, and therefore there was no chance of water getting through on to the bearing from the inside of the trough, which had been one of the main sources of trouble in the old design. The arrangement, of course, was open to one objection, namely, that it left a stretch of more than 2 feet without any rivets between the plates, and corrosion might take place between the plates at that point. The engineers in charge, however, were quite alive to that possibility, and it would, no doubt, have their special attention. A previous speaker had referred to the unequal spacing of the cross transoms in the cantilevers. That was due to the stopping of the internal viaduct near the end of the cantilevers where there was no longer sufficient depth to continue that form of construction. When the earlier work mentioned was being considered, discussions took place as to how the necessary strengthening of the floor should be carried out, and it was decided as a first step to put in additional transoms at those places in order to reduce the spans of the troughs to something corresponding with the spans in other parts of the structure. As the Author pointed out, the added weight of the new work had no appreciable effect on the structure, and, having had from time to time opportunities of examining it, he was glad to be able to say that in no parts other than those now dealt with did it show the slightest sign of weakness; it was in splendid condition. Mr. Brown.

Mr. C. F. BENGOUGH remarked that renewal had been necessitated not, of course, by any weakness in the troughs themselves, but mainly by the trouble that had arisen at the connection between the trough and the cross girder. In those circumstances, the renewal of all the troughs might be looked upon by some as a rather drastic cure. He had been privileged—for it was always a privilege to have anything to do with the Forth bridge—to take part in some of the later consultations with regard to what ought to be done, and the question whether it was possible to improve the connection between the troughs and the cross girders, in order to avoid the wholesale renewal of the former, was very carefully considered. Various measures were suggested, such as the introduction of a plate between the bottom of the trough and the cross girder, in order to get better riveting between the two, but it was felt that the design of the troughs was not satisfactory, and that anything that could be done in that direction would be merely patchwork. It was thought that it would be very much better when, as the Author pointed out, the necessary Mr. Bengough.

Mr. Bengough. plant and men with experience were on the spot, to undertake a complete renewal of the troughs and to put in somewhat stronger troughs. To prevent water from getting in between the way beams and the trough the general practice was to put some bituminous mixture between them. In the present arrangement oak or teak wedges were driven between the waybeams, and the troughs. Did the Author think that would be satisfactory? Was there not still a chance of moisture lodging in the spaces which would still remain at the bottom of the trough below the wedges? As to the cost of the work, he had been agreeably surprised at its lowness, considering the time at which the work was carried out and the fact that the proportion of temporary work to permanent work must have been fairly high. In 1919 and 1920 very high prices were being paid for girder work—anything up to £60 a ton—and £46 per ton of steel used seemed to him very satisfactory.

Mr. Macdonald. Mr. R. C. MACDONALD said the Paper had been of particular interest to him, as he also had the privilege of being associated with the work, both the manufacture of material, and, to a small extent, the work at the site. Having been responsible for the manufacture of nearly the whole of the material for the first part of the contract, he thought it might be of interest if he made a few remarks on the difficulties encountered in connection therewith. The section of trough in *Figs. 14* (p. 138), seemed very simple to manufacture, and so it would have been if the steel-makers had been able to deliver the sections as shown, namely, square and level in each member; but as a matter of fact, when delivered, in some cases the flanges were splayed outwards and the web was concave on the back, in others it was just the reverse, and in some channels both faults were combined. The Author pointed out the necessity for having as perfect a bearing as possible between the top angle of the transom and the bottom of the trough, and, as had also been pointed out, for a considerable distance there were no rivets connecting the trough or the bearing plate to the main angles of the transom. It was therefore essential that the lower side of the channel should be absolutely flat, and also that it should be perfectly level with the bottom flange of the vertical channels. To obtain that result it was necessary to devote a great deal of time and labour to straightening the channels—particuarly the bottom channel, for it was necessary that the lower side of the web should be absolutely level. The flanges had also to be square with the bottom in order that the vertical channels should stand plumb. The straightening of those channels had been no small task, and special blocks had to be made and other tools improvised for hydraulic presses, to straighten out the webs and flanges. The channels having been straightened, a start was made with the erection of the troughs on specially prepared blocks, carefully levelled. The troughs were assembled on those blocks, and great care was taken to ensure that they should be kept out of winding. Even then the task was not finished; there was still another difficulty, namely, in the riveting. The whole of the work done in setting the troughs up so carefully might have been upset if great care had not been taken. The method adopted throughout was to put rivets in at intervals all along the trough, so that no marked local heating took place at any time. That prevented further distortion of the troughs. Should it ever be necessary to renew a work of the same size and description, it would certainly provide a better job if the flanges of the bottom channel were rolled slightly heavier and machined from end to end. He did not think it would involve more work or expense than had been entailed in making the flanges absolutely square and straight. Probably a machine built on the lines of a draw-bench, with two milling-cutters and suitable guide-rollers, would do the work cheaply and expeditiously. Mr. Macdonald

Mr. G. A. GARDNER observed, with regard to the remarks of a previous speaker as to the inadvisability of incorporating one of the troughs in the main girder, that he took it the designers of the bridge had in mind the fundamental desideratum of carrying the load directly, with a view to the reduction of weight, which, of course, was a very important factor in so large a bridge. In this connection he believed that the rolling load on the bridge accounted for only about 16 per cent. of the total stresses in some of the primary members, and it would therefore seem to be correct policy in such a bridge to incorporate as much as possible of the secondary framing in the main girders. Looking at the diagrams, it would seem impossible for derailment to take place without the top flange of the girder being annihilated, although it had been suggested that the incorporation referred to had aimed at preventing damage from derailment. The difference in deterioration between the troughing in the viaduct and that in the main span, mentioned by a previous speaker, might have resulted from the fact that the dynamic increment of stress from the live load might be less in the longer spans of troughing than in the shorter ones; that was to say—contrary to the purport of one speakers' suggestion—the shorter the span, the greater the effect of the dynamic increment caused by the live load, and the longer the span, the less that effect would be. It might also happen, of course, that in some instances the "romp" Mr. Gardner.

Mr. Gardner. of the rolling stock over the rail-joints would synchronize with the period of the natural vibration of the span, and thereby set up, as had been observed by him, very harmful stresses.

Mr. Wilson. Mr. J. S. WILSON remarked that the glamour surrounding everything connected with the Forth bridge rendered a Paper such as the Author had submitted extremely interesting to many. The fact that so little of a detailed nature had been written with regard to the bridge rendered new details of the kind furnished in the Paper very acceptable. The reference to the design of the bridge came rather as a shock to some who had regarded it as representing the acme of perfection. As one who had had considerable opportunities of seeing some of the drawings and calculations relating to it, he thought it would be well to remember that, as far as design went, the Forth bridge had as much care and as much mathematical ability put into it as any structure in existence. Many would have seen the plate on the abutment of the bridge, on which appeared the name of Allan D. Stewart, M. Inst. C.E., who was a ninth wrangler at Cambridge and an extremely able engineering mathematician. Anyone who looked up Mr. Stewart's Paper[1] would find there a few details as to the method adopted, which was the strain method. All the strains in the different members were calculated and plotted. Moreover, the building of the bridge had resembled the growth of a tree more than anything else. Every deflection was measured and every stress kept track of, and to see some of the work involved at the time the bridge was built gave one the impression that there was not a haphazard bit of design in any detail of it. He had been glad to hear Mr. Brown mention that in no other detail had any weakness been discovered. With regard to the floor, he thought it would be agreed that, as far as saving weight was concerned, a neater and more econonomical system could not have been devised. The Author and all those who had worked with him were to be congratulated on getting the work accomplished during the war period. During the war the bridge was regarded as very vulnerable, and all kinds of suggestions for its preservation were made to those responsible, the consideration of which must have occupied a great deal of their time. One suggestion he had heard was that it should be protected against damage by aircraft by covering it with armour plates! It would have been very useful to those who had tried to get at the causes of the fractures and failures which had been described if slightly more detail had been given in the Paper with

[1] "Stresses and Deflections in Braced Girders," Minutes of Proceedings Inst. C.E., vol. cix, p. 269.

regard to the disposition and number of rivets. The Author stated Mr. Wilson. that many of them had worked loose, but the rivets not being shown, and the dimensions not being given, it was impossible for anyone to arrive at conclusions as to what should be avoided in future designs of similar type. If details of strain measurements on the troughs could be published they would be extremely interesting, because the inner trough, being rigidly connected to the floor and parallel and fairly close to the upper booms, would take the stress in the main girder due to the load, and some of the stress would almost certainly be transferred to the troughs through the very stiff flooring. Whether as much as ought to be transferred to it had actually been transferred he did not know; but the measurement might lead to a reason being found for the horizontal movement between the transoms and the troughs, which might possibly be due to the contraction in the length of the top boom, due to stress caused by the weight of the train being only partially transmitted to the troughs. He regretted that the test carried out on the sample trough had not been made with more scientific exactitude. If the load had been applied in the position of the rail, instead of on beams laid across the top flanges of the trough, the amount by which the top edges of the trough moved inwards or outwards could have been measured. That, apparently, was an important item in connection with the loosening of the rivets in the brackets. One other matter—obvious when pointed out, but often overlooked—was that the width of a rail-trough was comparable with the width of the head of the rail, and the weight from the wheel might be on the inside or on the outside edge of the rail, so that the distribution of weight between one side of the trough and the other could vary considerably. That had become very apparent in some of the tests carried out by the Ministry of Transport, where on a rail-trough girder certain stresses measured at crawling speeds and at high speeds were very different. That seemed to indicate that at crawling speed the load came on one edge of the rail and at high speed on the other edge, so that it was almost impossible to say what the difference in stress might be due to. Perhaps that might be responsible for some of the trouble in the case under consideration. He hoped the Author would be able to give further information with regard to the riveting, because, as several speakers had pointed out, the bearing stress might have been high, and additional particulars would be for the benefit of future work.

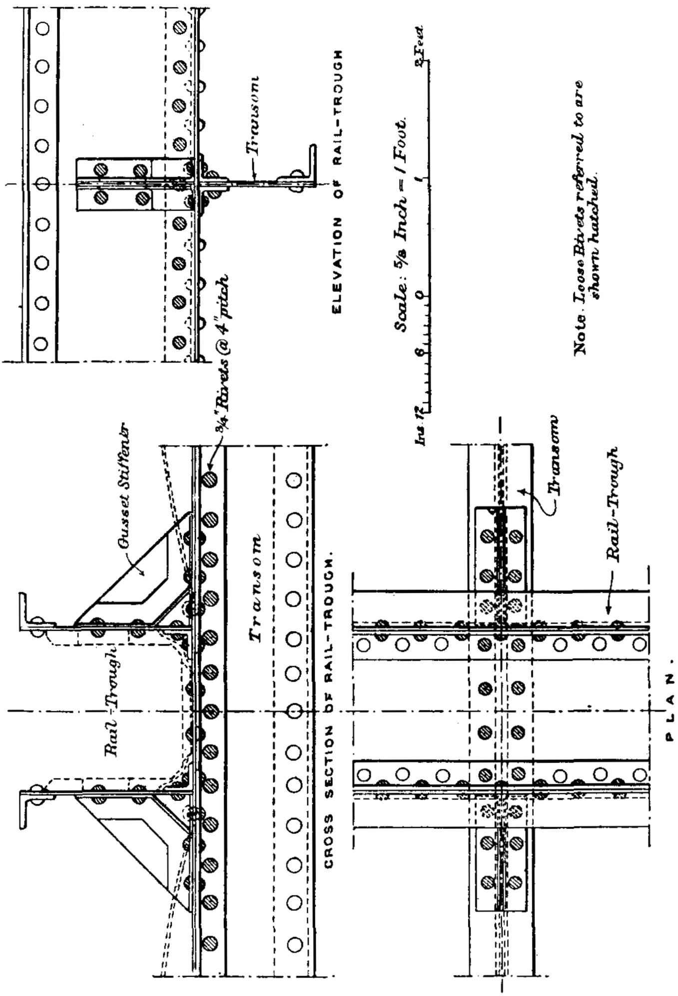
Mr. GERALD FITZGIBBON said he was under the impression that Mr. Fitzgibbon. when the bridge was designed, in 1881, 9 years before it was opened to traffic, the weight of the heaviest locomotive on the North British

Mr. Fitz-gibbon. Railway was considerably less than $77\frac{1}{4}$ tons; in fact, he believed it was about 56 tons, so that the increase in weight between the time when the bridge was designed and 1908 would be a little over 100 per cent. instead of 55 per cent.

The Author. The AUTHOR, in reply, remarked that Mr. Grierson seemed to be rather pessimistic about the connection between the new trough and the transom. After the experience he had had of maintenance of the original arrangement, and of the damage at the seatings due to direct connection of the trough to the transom, he would never recommend the adoption of the same arrangement again. He had closely observed the new arrangement, and believed it would give little cause for regret: it formed a good connection, with no sign of weakness. The present speed-limit on the bridge was 40 miles per hour, and he thought there would be many complaints from the traffic department if that speed were reduced. In 24 hours something like 200 trains crossed the bridge, and therefore it would not be practicable to have a lower speed-limit. He did not think, in fairness to the contractors, he could state in detail how the cost of the work had been arrived at. He believed his directors were very well satisfied with the whole arrangement; and keeping in view that the work had been carried out during the war period, he thought £45 per ton was a very reasonable figure. He thought Mr. Gribble had overlooked the fact that most of the trouble had been caused by lack of rigidity in the internal viaduct cross transoms, which were only about one half the depth of the transoms on the approach viaducts. There was some deterioration in the troughs on the central girder spans, but not to the same extent as that on the troughs on the internal approach viaducts. Renewal of the troughs on the internal viaduct had become necessary, and as a large quantity of expensive plant and high-pressure air-pipes had to be provided for that, and also having regard to the fact that men with experience of the work were on the site, it had been decided as the most economical course to complete the work on the whole bridge. He thought that had been a wise decision. He had obtained much information of the relation between calculated and actual stresses, from tests made, with the latest instrument for that purpose, on a number of bridges, but he had not investigated the matter in great detail in the instance in question. He could say, however, that the stresses so observed were lower than the calculated stresses, probably owing to the assistance which the trough obtained from the oak waybeam and from the rail itself, and on account of considerable distribution of the stresses among the different members of the floor, a matter which he thought demanded more consideration than it had received in the past. He agreed with Mr. Brown that comparison of the total weights of engines was not a correct criterion; he had given the weights merely to show in a direct way the large increase that had taken place. It was true, as Mr. FitzGibbon had said, that the

The Author.

Figs. 18.



weight of the heaviest locomotives when the bridge was begun was about 56 tons; but in designing the bridge the actual weight taken was 73 tons, and the comparison with an engine in running order of $77\frac{1}{4}$ tons was very close. With reference to Mr. Bengough's

The Author. remarks, he would not go so far as to say that the trough was actually sealed, but a great improvement had been made, and very little water could now get in. The two drip pipes provided in the bottom channel would drain away any water which might get in. He had been very glad to hear Mr. MacDonald's practical remarks. Messrs. Arrol had carried out their work with great credit, and although they met with many difficulties, they had overcome them very well. Mr. Wilson's remarks in regard to the care and skill exercised in the design of the bridge were most interesting and were reflected in the excellent condition of the structure to-day. With regard to the loose rivets, these were always discovered at the seatings and in the top main angles of the transom directly below the troughs, where about a dozen rivets were effected (*Figs. 18*, p. 153). That trouble might be due to the distribution of the stress, as one speaker had suggested, but it was a very difficult thing to determine. His own view was that the whole trouble was due to lack of rigidity in the cross transoms as compared with the main girders. In the test carried out on the sample trough, the load had been applied on the rail, a timber way beam and rail having been previously fitted in the trough for that purpose. The trough was supported on bearings 22 feet 6 inches apart, the amount of widening of the trough being shown in columns Nos. 5 and 6 of the Appendix. The section modulus of the trough tested was 197 units (inch^3).

Correspondence.

Mr. Cornick. Mr. H. F. CORNICK remarked that the Author ascribed the primary cause of defects in the connection of the troughs to the transoms to the effect of the increased loads passing over the floor of the bridge, and to the lack of rigidity of the inner compared with the outer troughs. Mr. Cornick was strongly of opinion that the most important cause of the troubles alluded to could be attributed not so much to the effect of the increased loads, but to the "hinging" of the troughs, due to their continuity at the points of support on the transoms, the hinging being caused by the advancing trains loading first one span of trough and then another throughout the length of the bridge. In certain places on the bridge the depth-span ratios of the rail-troughs, as originally built, appeared to be somewhat less than the ratio now usually accepted for rail-bearers. Moreover, there would probably be considerable local deflection in