

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<sup>3</sup>).

### Correspondence.

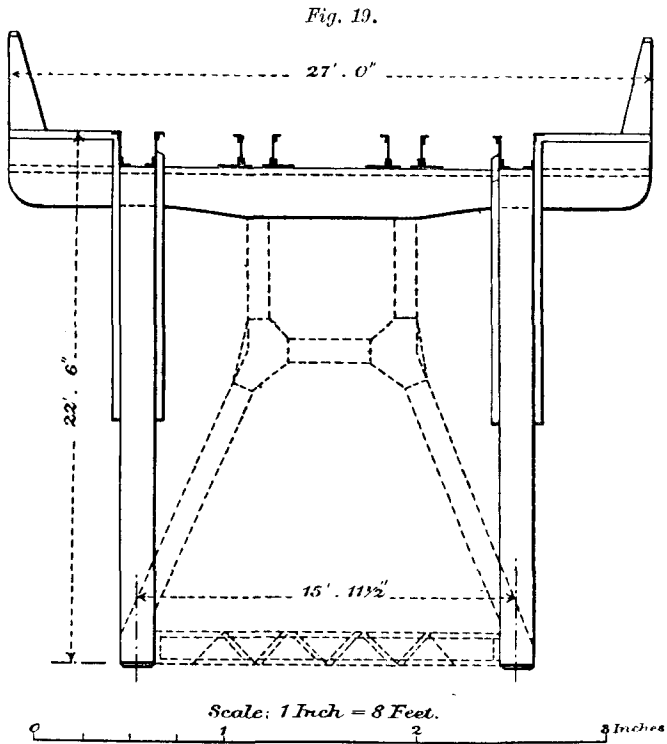
Mr. Cornick. Mr. H. F. CORNICK remarked that the Author ascribed the primary cause of defects in the connection of the troughs to the transoms to the effect of the increased loads passing over the floor of the bridge, and to the lack of rigidity of the inner compared with the outer troughs. Mr. Cornick 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

the cross transoms themselves, which would add, of course, to the total deflection of the troughs under load, by altering their levels of support. Such conditions in continuous girders produced deflections and stresses, the amounts and character of which were very difficult to calculate. He could imagine that the sagging was the cause of the cracking of the buckled plates where they were riveted to the rail-troughs and to the transoms in the neighbourhood of the former, also of the "working" of the rivets in those places and of the horizontal movement. What had been done in adding further transoms and in deepening their top booms would tend to reduce the deflections, which was undoubtedly the first thing to eliminate as far as practicable. The end fixing of ordinary rail-bearers into the cross girders of a through railway-bridge was very rigid, and he suggested, as an alternative to the right-angled support, two brackets under each end of the troughs, composed of gusset plates and angles riveted together, and to the bottom flanges of the trough-channels and to the sides of the transom top booms. The bearing-plate on the transom top flange could be thickened up to, say,  $\frac{1}{2}$  inch and extended in the form of a cap plate as far as the extremities of the gusset plate and angles. Rivets passing through the rail-trough channel flanges would secure the whole together. This arrangement would have the effect of giving much greater fixity to the connections of troughs to transoms than the right-angled side support and seating-plate adopted, which latter appeared to be more in the nature of a lateral support to the troughs. A somewhat parallel case with which he had been intimately connected was the suspended booking-hall floor at Victoria Station (District Railway). That floor was composed of continuous girders of small depth compared with the length of their span, being of a similar section to the rail-troughs of the Forth bridge. The floor itself was formed of steel troughing riveted to the top flanges of the continuous trough girders. The girders themselves were suspended over the permanent way and platforms from upper main girders by means of circular steel ties 6 inches in diameter. The floor was called upon to sustain a very heavy and fluctuating live load due to moving crowds. To provide for the proper movement at the points of support of the girders, due to one span being loaded and the next or alternate spans unloaded, and to other conditions of irregular loading of the spans, the connections between the steel suspending-ties and the girders were designed as cast-steel trunnions, the webs of the trough girders being thickened up by means of doubling plates to provide the necessary bearing-area for the trunnion-pins. He would not suggest that such a method might have been

Mr. Cornick.

Mr. Cornick adopted in the case under discussion, but he merely cited it to point out the somewhat elaborate efforts made to provide for the hinging movement in the structure briefly described, by allowing it in that case to take place freely.

Mr. Gardner. Mr. A. C. GARDNER referred to the statement that one of the primary causes of the defects in the floor-system was attributable to the lack of rigidity of the inner as compared with the outer rail-troughs. He asked whether it had been found that, where the



method of supporting both the inner and outer troughs was similar, as in the case of the central girder spans, the fractures between the rivet-holes as well as the loosening of the rivets was less pronounced than in those cases where the method of supporting the inner and outer troughs was quite dissimilar, as in the approach spans. In the case of the internal viaduct the measures adopted for strengthening by the deepening of the cross transoms undoubtedly added considerably to the stiffness of the floor, and it was difficult to see

what better remedial measures could have been employed to give Mr. Gardner. a more rigid support to the inner troughs; but on the approach viaduct spans, beyond the addition of web-stiffeners to the cross girders in the immediate vicinity of the inner trough, it did not appear that any greater rigidity had been secured in the floor as a whole. Seeing, however, that it was considered necessary to strengthen the main girders in these spans at the same time as the strengthening of the floor was undertaken, and that that had been done by bracing the girders at every panel-point, instead of at every other one, as well as by tying the bottom booms together, he asked whether the question of lengthening the rail-troughs from 7 to 10 feet had been considered. Had that been done, it would seem to have been possible to have constructed the bracing in such a manner (as, for instance, in *Fig. 19*) as to have given direct support to the cross girders immediately under the inner rail-trough and so to have added considerably to their rigidity, which was found to be lacking. By such means one cross girder in three might have been eliminated altogether, which would have gone some way towards compensating for the additional weight needed in the bracing. His own experience suggested that such a course might have presented considerable practical difficulties of which he might not be aware, but he would like to know if the question of making the new cross bracing contribute to the rigidity of the floor had been considered, seeing that it had been taken in hand at the same time as the repairs to the floor.

Mr. GUSTAV LINDENTHAL commended the careful and cautious Mr. Lindenthal. manner in which the difficult work had been planned and carried out. The principal causes of trouble had been removed as effectively as was possible, but there still remained the possibility of trouble in the future from sulphurous water and dirt collecting in the spaces between the sleepers and the sides of the rail-troughs, and gradually working through loosened joints to between the trough and the transom, especially as they were not directly riveted together. Grit working in between the sleeper and the bottom of the trough also might cause in time abrasion of the latter as it had done in the past. The drain-pipes fitted in the troughs might easily become clogged by dirt or by freezing in winter. He was of opinion that an open construction, avoiding pockets and affording possibility of easy inspection and painting, would have been preferable, although possibly more expensive. The Author stated that the weight of the heaviest engines had increased by 55 per cent. and that axle-loads had increased by 29 per cent. in 18 years after the completion of the bridge. In view of that it would seem that

Mr. Lindenthal. the rail-troughs should have been strengthened by more than only 37 per cent. It would have been possible to do that at comparatively small additional expense. In the United States weights of engines had more than doubled in the last 25 years; axle-loads were now exceeding 40 tons. While such large increases would not take place on English railroads, yet some increase in present weights, and particularly in axle-loads, were not improbable and should have been provided for. It would be useful to know whether any derailments had occurred on the bridge, and whether the through system had proved a safeguard. A few notes on the cost of painting of the bridge would also be of interest.

Mr. Nicholson. Mr. J. H. NICHOLSON, who was resident engineer for the contractors for a period, complimented the Author on his lucid description of the work. The condition of the old troughs when removed was very interesting, particularly in the regularity of the deterioration. The troughs acted as continuous girders over the transoms, and for about 2 feet 6 inches to 3 feet on either side of practically every transom the rivets through the bottom angles were loose. The looseness was at a maximum over the transom, where some rivets were eroded down to the thickness of a pencil, and diminished on either side. There was a good deal of erosion of the bottom plate, where it rested on the transom, in the bottom angles, and where the side plates bore on the bottom plate; and some of the bottom plates were cracked. There seemed little doubt that those defects had occurred subsequently to the loosening of the rivets, and that the latter had been the cause of the former. Leakage of water past the loose rivets would accentuate the erosion. It would be of interest if the Author would state the arrangement and scantling of the rivets in the old troughs, and the shear and bearing-stresses under the rolling and dead loads occurring in 1890 and in 1908, assuming in the latter case that the rivets were tight. The trough between the areas mentioned were generally in good condition. It would be interesting to follow this point still further, and to consider that, had the trough been more heavily riveted over the transoms, it would have stood up to its work successfully, although it was of light section. He would not suggest that such a repair could have been carried out in place of the present reconstruction. From what he had seen of the old troughs, they had reached such a state that it would have been impossible. But in the original design such a course might have been provided for. This is a point which might have appeared at the time to be of minor importance, and yet it had proved sufficient to spoil the trough. There must be a rapid reversal of stresses under the rapidly-recurring wheel-loads

of a passing train, which would increase the stresses still further by Mr. Nicholson. impact. The provision of rivet-area in the connection of the side channels to the bottom channels in the new troughs was ample, and it would be of interest to have details, including the bearing and shear stresses. The reduction of time taken to fix the troughs on the Sundays was a good example of repetition team work—not often met with in bridge work. The sequence of operations each Sunday were practically the same, even to the number of rivets closed. The workmen were of the usual type, chiefly gathered up in the district. At first the operations took 20 hours to complete. When fairly running, the time was soon reduced to 16 hours, and later it was brought down to 10 hours. Thus, if a piecework rate had been fixed even on the 16 hours basis, the men would soon have been making one and two-thirds time on that rate. A system of task work on such lines had been instituted during the contract, and it had been of great advantage to the men. At the same time it had reduced the time during which single-line working was necessary.

Mr. W. A. TAIT congratulated The Institution upon having Mr. Tait. received so interesting and thoroughly practical a Paper, which was particularly welcome on account of the frank way in which the facts were stated. The Paper was also of interest to him personally, because as a near neighbour he had enjoyed, through the kindness of Sir Benjamin Baker, Sir William Arrol, and Messrs. Allan Stewart and Walter Meik, many opportunities of visiting the bridge during construction. Since the opening he had been a frequent traveller over the bridge, and had also been privileged to accompany Mr. Fraser on his rounds.

As one of the Members of the Institution who visited Canada and the United States in the autumn of 1904, under the leadership of the late Sir William White, he recalled that on the occasion of the visit to the site of the Quebec Bridge the engineer-in-charge, when explaining his drawings, said: "You people in the Old Country put a great deal too much steel into the Forth bridge. We are going to show you how much less would have done." The unfortunate failure of the Quebec bridge was well known, but it ought to be recorded that this visit and conversation took place about 2 years before trouble began to be experienced with the floor of the Forth bridge, otherwise a warning might then have been given as to the necessity of providing steelwork for reasonable future requirements.

As The Institution had not previously published a general account of the structure of the Forth bridge, he hoped that Mr. Fraser would see his way to write an additional Paper giving information,

Mr. Tait- accompanied by detailed drawings, to explain the general arrangements at and near both the inner and outer ends of the cantilevers. Such a Paper might deal with the available records of vertical and lateral movements at the free ends of the cantilevers and also of the central girders.

Without going into that question, however, it would appear that the original roadway of the Forth bridge must necessarily be rather troublesome to maintain as one rail of each line was, in general, directly carried on a main girder of considerable depth and stiffness, while the other was in fact supported by a shallow trough carried on a comparatively light cross transom, which in turn was supported on the main girder. Put shortly, the two rails on either side of the 6-foot way must have had more freedom in a vertical plane than the outer rails. The resulting deflection would be the more marked as the axle-loads increased, and other complications would probably also ensue.

The original arrangements for draining the troughs were open to objection, as also the placing of the buckle plates so as to be convex upward. Moreover, the moss litter used in the troughs might have permitted some lateral play to the way beams carrying the rails, which were at first only 28 feet in length. The individual items above detailed were objectionable in themselves, but their cumulative effect might have been considerably worse, and particularly so on the inner troughs, which had necessarily more freedom than the outer ones.

It would be of interest if the Author would produce any measurements he might have of longitudinal expansion of the inner and outer troughs on a summer's afternoon.

The indentation of the inner troughs and the transoms which carried them, together with the starting of the rivets, indicated the place of greatest disturbance. It might be that the bearing area originally provided was insufficient for the increased axle-loads, but the relatively greater freedom of the inner troughs probably facilitated grinding action caused by grit and moisture getting in between the buckle plates and the transoms.

The steps taken in regard to renewals seem generally to have proceeded on right lines. The doubling of the length of the bridge-rails had halved the number of rail-joints, and thus must have reduced the hammering effect of heavy axle-loads on the floor of the bridge. The roadway was fortunately easily accessible from above and below.

By no means the least of the alterations was the new arrangement whereby right-angle plates had been introduced at the junction

between troughs, buckle plates and transoms, with the minimum of attachment between the troughs and transoms. The result was that no suggestion could now be made as to possible self-straining of the structure of the roadway, and, as the Author very properly pointed out, it was now practicable to carry out repairs on the connection without disturbing the permanent way, which was impracticable under the original arrangements. Mr. Tait.

Mr. T. G. HOWES THOMAS remarked that the chief causes of the deterioration of the floor were the lack of adequate provision for the rapid disposal of surface and rain water, the corrosion of the troughs as a consequence, the frictional wear due to detritus, the excessive shear on the rivets due to unequal deflection of the transoms, and the usual expansion and contraction which took place in all steel structures of large dimensions. The remedy adopted, however, was only partial, as the chief causes of wear and corrosion remained. Troughs would still be temporary water channels in times of rain, and a certain percolation was bound to take place. Vibration would probably cause paint-fracture, and excessive heat would loosen the timber, opening up surfaces closed in wet weather, so that ultimate corrosion was likely to occur again. It was highly probable, therefore, that renewal would have to be considered again in 15 or 20 years' time, if not before. Wear was bound to occur where one wheel-load was directly over a practically rigid structure, e.g., the main girder, and when the other line was carried on a series of light transoms which must deflect more than the main girders, producing shear stresses at the passing of each train. That was evidently the cause of the greatest wear due to loading. A great deal of the wear between the troughs and transoms due to shear would have been avoided, had the 5-foot ways been carried centrally over the main girders. Taking the case shown in Fig. 10, Plate 2, where the main girders were spaced 15 feet 11½ inches apart, by the proposed arrangement the 6-foot way would become 11 feet 3 inches, and the footway would be carried a little farther out. The stresses would be more regular with consequently less wear and maintenance. The extra width would not materially affect the cost on such an enormous structure, especially as it was 120 feet wide in places. The keeping to a definite 6-foot way was neither always necessary nor advisable in bridges where plenty of width was available. The rigidity of a sleeper, whether parallel to the rail or at right angles to it, was of paramount importance in all railway work, especially on bridges; the designers had that point in view when designing the troughs with side stiffeners. It was, however, well known that

**Mr. Thomas.** movement of permanent way due to trains rarely occurred on straight sections of line, although it was distinctly noticeable on curves. Track movement on the straight length of the Forth bridge would be inappreciable, so that other methods of laying the permanent way would have been quite suitable. Practically all the troughing had been removed, made good, and renewed where needed. That being so, and in view of the causes of wear being known, why an alternative floor had not been considered and laid down instead of one with the inherent defects of the old was difficult to understand. If other designs had been considered, it would be interesting to know from the Author why they had been discarded. The first essential in all bridge work was to keep out as much water as possible and get rid of it quickly. Trough design did not do that, and other schemes would answer better. Watertightness was almost impossible on a vibrant steel bridge, but it could be reduced to a minimum with some methods of construction.

**Mr. Train.** Mr. J. C. L. TRAIN remarked that he had been instructed some months ago by Mr. Charles J. Brown to investigate the possibility of establishing a relationship between the calculated stresses and the actual breaking stresses in the case of the troughs referred to in the Paper; but he had not succeeded in doing so. As the result of what little he had done he suggested that many who advocated the testing of structures to destruction were apt to consider a structure as a test-piece which would fracture at the proper moment and provide definite data upon which to work. It was very difficult, however, to obtain the relationship between calculated stress and breaking stress by testing a bridge to destruction, because a built-up member would seldom, if ever, break, but would distort to such an extent that the application of the real breaking load would be rendered impossible.

**The Author.** The AUTHOR, in reply, remarked that he appreciated Mr. Cornick's remarks in regard to the effect of the "hinging" action on the troughs, due to their continuity at the point of support on the transoms, but, from close observation of the behaviour of the floor under load, he was of opinion that this was of much less importance than the effect of the increased loads and the lack of rigidity of the inner as compared with the outer troughs. A method of support on the lines suggested had been, along with other methods, given full consideration, and discarded in favour of the right-angled support, for the reasons stated in the Paper.

With regard to Mr. Gardner's remarks, it was the case that where the method of supporting the inner and outer troughs was similar, as in the central girder spans, the fractures between the rivet-holes

and the loosening of the rivets were less pronounced than in the inner troughs on the approach and internal viaducts. The transoms in the approach spans were deeper and stiffer than the transoms in the internal viaduct, and accordingly the provision of additional web stiffeners immediately beneath the troughs was considered to be sufficient. In any case, the new cross bracings between the main girders of the approach spans were provided to give additional lateral stiffness in those spans; and to make the new bracing contribute to the rigidity of the floor and interfere with the cross transoms, as suggested, would have presented unsurmountable difficulties under traffic conditions.

He appreciated Mr. Lindenthal's remarks in regard to the manner in which the work had been planned and carried out. Special precautions had been taken to prevent water and dirt from getting between trough and transom, by the adoption of continuous creosoted-timber packings in place of moss litter and tar packing in the spaces between the timber waybeam and the sides of the rail-trough, by caulking the top edges of the bottom channel, by the adoption of a close rivet-pitch, and by the provision of drip-pipes in the bottom of the trough. No derailments had occurred on the bridge.

In reply to Mr. Nicholson, the maximum shearing and bearing stresses in the riveting due to dead load and the live loads in use in 1890 and 1908, assuming impact, were the following :—

Original Troughs.	1890 Loading.	1908 Loading.
	Tons per Square Inch.	Tons per Square Inch.
Shear . . . . .	$5\frac{1}{2}$	$7\frac{1}{2}$
Bearing . . . . .	$12\frac{3}{4}$	$17\frac{1}{2}$
New Troughs.		
Shear . . . . .	..	$3\frac{1}{2}$
Bearing . . . . .	..	5

The Author was of opinion that, while heavier riveting of the troughs over, and on each side of, the transom might have proved more satisfactory, it would not of itself have prevented the damage which developed. The rivets in the new troughs connecting the side channels to the bottom channels were  $\frac{3}{8}$ -inch in diameter, in two rows, the top row being at  $2\frac{1}{4}$  inches pitch and the bottom row at  $4\frac{1}{2}$  inches pitch.

The original floor of the Forth bridge was, as stated by Mr. Tait, difficult to maintain, for the reasons mentioned, but the Author was of opinion that the new work would give much more satisfactory results in this respect. The provision of drip-pipes in the bottom of the new trough would overcome the trouble previously experienced

The Author. of disposing of surface water which might find access to the inside of the troughs. The reversal of the buckle of the floor-plates had made a considerable improvement in the drainage of the floor between the troughs. The moss litter and tar which had been used in packing the space between the timber waybeam and the sides of the troughs was not so effective as were the creosoted timber packings in maintaining the waybeam in position. The main objection to the moss litter packing was the fact that it did not effectively prevent surface water from finding access to the inside of the trough. He regretted that no measurements of the relative longitudinal expansion of the inner and outer troughs in summer weather were available.

Mr. Thomas had not quite appreciated the fact that the outer rail-troughs formed the top boom of the main girders in both the approach spans and the internal viaducts: to have altered these members would have involved very serious interference with the fabric of the bridge and with the traffic-arrangements, which, of course, had been out of the question. Different methods of construction had been very fully considered, and the Author did not now consider that a more effective method of carrying out the work could, in the circumstances, have been adopted. He was confident that the new floor would have a much longer life than had the old.

He quite appreciated Mr. Train's remarks, as he had experienced a similar difficulty in establishing a satisfactory relationship between the calculated stresses and the stresses obtained from the deflections of the trough under test.