

Paper No. 6537

Three prestressed concrete railway bridges†

by

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Discussion

Mr A. N. Butland (Chief Civil Engineer, British Railways, London Midland Region), said that these bridges exemplified the method adopted to deal with the present heavy load of work falling on his Region. The bridges were conceived in type by railway staff, the experimental work to prove their feasibility and the initial calculations to confirm their proportions were all done in his office, but the detailing was put out to contractors, and he had found this method satisfactory.

68. The work at Fairfield Street had been necessitated by the need to lengthen the main line platforms, and this could only be done by swinging the tracks carried by the Fairfield Street bridge on to a new alignment at a much flatter angle of skew, and whatever construction had there been adopted would have had perforce to carry a passenger platform to receive the end of a footbridge on the platform and to carry buildings on that platform.

69. Prestressed concrete seemed the only solution and models were tested on the basis of preliminary calculations, completion of the work being passed to an enlarged team as mentioned. So an imaginative concept became a practical proposition. It was expensive, but the only way of meeting the operating requirements.

70. Several ways of doing the job had been considered. Clearly, it was necessary to have fairly heavy staging at the site, which was very busy during the day with trolley-buses, motor-buses and lorries, but because of the variation in width of the bridge throughout its length the use of precast members was not economic and the *in situ* prestressed design was adopted.

71. Mr Butland asked whether the Author had in mind any particular lessons learned that would alter procedure in any way if these bridges or similar ones should be started again?

Mr A. Lloyd Owen (New Works Officer, British Railways, London Midland Region), said that twenty-two bridges, including the three mentioned in the Paper, were reconstructed as part of the electrification work between Oxford Road, London Road, and Slade Lane Junction section of the Manchester-Crewe Line. This section was only 2½ miles long, mainly on bridges and viaducts; and the work consisted of redesigning and re-laying about 14 miles of track, mainly points and crossings, reballasting all tracks, reconstructing the London Road and Oxford Road stations, installing new signalling and overhead electrification, 80% of the foundations of the later work being placed by the Chief Civil Engineer's Department.

73. He had had the privilege of carrying out all the civil engineering work, and after careful planning it had been agreed that it was possible to carry out all individual jobs within 36 hours at the week-ends and, except for periods of 8 hours, to maintain an up and down line to London Road. The General Manager had agreed to that restriction. The rolling-in method of constructing the bridges and the use of the contractors' new 65-ton road crane had greatly assisted them in coming to that decision.

† Proc. Instn civ. Engrs, vol. 20 (Sept. 1961), pp. 1-18

74. 20 ft of headroom was required from the road surface to the underside of all bridges between kerbs, in accordance with an Act of Parliament relating to the original building. Further, since there were weak and low road bridges on the east and west of Manchester, the City Engineer had said that all heavy and large road loads would have to pass under these new bridges, except at agreed times at week-ends; and two passage ways 16 ft high and 9 ft 6 in. wide had to be maintained for that purpose. The bridges were designed and the temporary works built to suit these requirements.

75. Supervising the work were two Resident Engineers, two Assistants and four Clerks of Works, with clerical assistance on site. To cover all the work plus pre-planning, general co-ordination, dealing with possessions, and other tasks they had had the assistance of a small modernization section in his office $\frac{1}{2}$ mile from London Road.

76. Bridge 23 was constructed first to enable Slade Lane Junction to be realigned. The site had room on the Stockport side for a restricted working space and the casting and rolling-in was done from that side. The concrete sections, being 8 ft wide, suited both road and rail vehicles. The depth of the beams had made it necessary to reduce the abutments to accommodate the bearings. This was done by supporting the tracks, in twos, on rail beams.

77. To keep to the General Manager's time schedule at week-ends, the box girders were waterproofed and ballasted and the track partly laid before launching them. Because of the closure of one road footway for a period there had been a strong claim for loss of trade from the shopkeepers, which was resisted. The job took 11 months, but week-end work affecting the track was confined to a period of 5 months,

78. Bridge No. 30 was the next large bridge to be built to permit realignment of the tracks into Longsight locomotive sheds. The site was very congested and one of the main Manchester sewers had to be diverted to allow the centre pier to be built. A small factory had to be removed and temporary premises provided; and an adjoining owner's reconstruction scheme was stopped to enable working space to be provided on the Stockport side of the bridge. A public house on the Manchester side, which projected beyond the face of the abutment wall, added to the difficulties of rolling in.

79. Some thought had had to be given to the method of lowering the slab from the casting platform to the rolling-in level, since it was calculated at site that the supporting universal beams would deflect, causing uneven loads on the $1\frac{1}{2}$ -in. high-tensile steel rods. The load on each was calculated and each rod tested, the nuts being adjusted with torque spanners. The top nuts and rods were marked and were adjusted as the supports to the slab were removed. The sixty-four rods were then lowered in unison to keep the slab on the same plane throughout its area.

80. The whole job had taken 12 months but work affecting the track was reduced to a period of 7 months. This period was 1 month longer than schedule owing to continuous fog for 5 weeks.

81. The Fairfield Street bridge reconstruction had been timed to be built in 15 months, including the station buildings. Taking the load off the supporting formwork and supporting it on jacks had gone extremely well but, as expected, the final deflexion of the structure was not obtained at the time.

82. All three original bridges had been a cause of constant complaints owing to drainage problems, and the abutments were either cleaned or refaced after reconstruction.

83. One of the principal difficulties in the congested area was the volume of complaints about noise from compressors. That was alleviated by agreeing to work at certain hours and by reducing the noise by providing special maintenance for the machines, and placing them on rubber pads. Plant manufacturers should give that careful thought, since it had been found that the men worked better when the noise was reduced. To cover week-end complaints, the railway Public Relations Officer had given a full but concise description of the work to the press. That had turned complaints to more active interest and large crowds watched the work. Although they had caused difficulties, that had been preferable to the complaints.

Mr R. F. T. Kingsbury (Managing Director, Stressed Concrete Design Ltd), said that after considerable thought had been given to systems of prestressing, it had finally been decided that four systems would satisfy and fit into the different parts of the structure.

85. A slide illustrated four main beams, together with bottom slab, the top slab acting as platform. In the bottom slab there were employed 80 strands $1\frac{1}{2}$ in.-dia. in individual ducts, located in the top and bottom of this slab. Passing transversely through the slab were a series of Magnel-Blaton 40- and 56-wire cables. At platform level there were 40- and 32-wire Magnel-Blaton cables. In the four beams there were 48 multi-strand cables, $1\frac{1}{2}$ in.-dia. This was thought to be the heaviest type of multi-strand cable yet employed.

86. In the two main diaphragms the Lee-McCall system was employed. In the capping cables over the diaphragms the Freyssinet system was used, but the shear bars in the webs were Lee-McCall bars, located at various centres from 3 ft down to 21 in.

87. The housing of the multi-strand cable was a purpose-made metal *gaine* sheathing, the strands were fed off reels and winched through and finally laid into special grilles, each strand being separated from its neighbour, from the last design grille it was necessary to fan out into special trunking and from the end of this section into individual ducts. This was due to the troubles that would have been experienced from packing good concrete into a tapered area.

Mr P. S. A. Berridge (Assistant Engineer, Bridges; Western Region, British Railways), said that this was an instance where late steel deliveries had been an immense benefit to British Railways, to the City of Manchester, and to the engineers of the country. The railway had three fine bridges likely to cost extremely little in the future.

89. Manchester owed a debt to the Author and to British Railways for the displacement of slummy-looking old bridges by spans of very pleasing design and lines. Those who wondered how to improve the looks of pilasters should compare Fig. 8 with Fig. 11, and Fig. 12 with Fig. 15. The continuation of the handrailing across the top of the pilaster, seen in Fig. 11, was a particularly pleasing treatment and, incidentally, it provided a welcome refuge.

90. He did not doubt that steel would have been cheaper in first cost; but in the future there would have been the recurring cost of painting, always dependent on the human factor, in that the frequency of repainting steel bridges was too often left to the decision of someone to whom immediate savings might count more than the high costs of maintenance caused by neglect.

91. Prestressed concrete should need no maintenance provided the design was right and it had been made properly. Prestressed concrete had the advantage over steel that all the vital supervision was concentrated in the office, in the works, and on the site at the commencement of the life of the bridge.

92. In arriving at the value of railway assets, accountants ascribed a life of 60 years to a steel girder bridge and 75 years to one in reinforced concrete. Obviously, the figure for steel was too short. He thought that the life to be expected from a prestressed concrete bridge was 150 years and he did not consider that that figure was over-conservative. He had arrived at it after careful study of the means of failure.

93. The prestressing membrane had a factor of safety of 2 against failure under full design load. Concrete had a similar factor of safety of more than $2\frac{1}{2}$. Deterioration could be caused by (i) deterioration of the prestressing steel, (ii) failure of bond in pre-tensioned concrete or failure of anchorage in the post-tensioned beams, (iii) loss of freedom at the bearings, and (iv) failure of the concrete through chemical disintegration or alteration.

94. In the steel due allowance for relaxation would be made in the design of the prestressed concrete beam. The effect of fatigue was extremely low, the range of live-load stress not exceeding 7% of the total stress. The Author had drawn attention to the high

ratio of dead to live loading on the bridge. The greater that ratio, the longer a bridge would last.

95. In prestressed concrete, shrinkage of the concrete was unrestrained. Due allowance for shrinkage and creep was made in the design, and in any case that effect ended completely within two years of manufacture. Creep which was plastic flow unloaded the prestressing steel. This incidentally, was the opposite of what happened in ordinary reinforced concrete where the creep transferred the load to the steel and often initiated hair cracks.

96. The rubber bearings, unlike roller expansion bearings, were unlikely to want much maintenance. They were not exposed to direct sunlight and at the worst it would not be impossible to renew them.

97. It was conceivable that the carbon dioxide and sulphur dioxide mixed with the Manchester rain could have a solvent action on the lime in the concrete, but it was extremely unlikely that the effect of such action could be felt more than $\frac{1}{2}$ in. in from the surface of the concrete; and bearing in mind that the surface of the concrete was always under pressure from the prestressing force, the chances of internal attack from those acids was extremely remote.

98. He would not feel so confident if the concrete in the beams had been designed to carry any tension but it would be seen from the Paper that the Author had been careful to specify zero tension stresses under working conditions.

99. Having had the privilege of seeing the bridges at various stages of construction he had been much impressed by the quality of the workmanship and the excellence of the designs.

Mr A. Goldstein (Partner, R. Travers Morgan and Partners), said he had been particularly taken by Bridge No. 23 (Stockport Road). He wished first to ask the Author a question in relation to § 10. There he had stated the reasons leading to the adoption of prestressed concrete; and Mr Berridge had just spoken of the advantages of prestressed concrete in relation to maintenance.

101. Would the Author, having now had time to consider all aspects, choose steel or prestressed concrete if he had to do the whole job again, with a completely free choice and full availability of materials, assuming there was little in the comparative costs?

102. Secondly, there were presumably special reasons for having a steel plate over and under the rubber pads in some of the bridge bearings. That could be one of the weaker links in relation to maintenance. Could the Author say whether, apart from any special practical considerations, he would have any objection to omitting those steel plates and using rubber bearings only?

103. He was troubled by the statement in § 54:

"It was considered important that the final structure should always show a hogging profile under dead load and, therefore, a rather high creep value . . . was adopted".

104. He agreed that the line of the deck should always show a slight hogging, or at least not a sagging appearance. That problem was common to all bridges but he did not agree that by choosing a high value of creep, the desired effect could be guaranteed, because the deflexion would be due both to weight downwards and to prestress, presumably upwards; and in both cases creep was relevant. The difficulty lay in balancing the two. Could the Author expand upon that?

105. The point of particular interest in relation to Bridge No. 23 was the torsional section at the ends. It was stated that tests were carried out on a Perspex slab. It would be an extremely valuable addition to the Paper if the Author could give details of the test. Presumably it was a box model. Were stresses measured or deflexions? Could the Author also give details of any analysis used for evaluating the torsional stresses and deformations and combining them with the normal beam and prestress stresses.

106. It was the intention in the design to have a three-span bridge, and since the side spans were very short, sufficient load had to be induced on the end supports to ensure



FIG. 18.—FAIRFIELD STREET BRIDGE AT AN EARLY STAGE



FIG. 19.—FAIRFIELD STREET BRIDGE AT AN ADVANCED STAGE

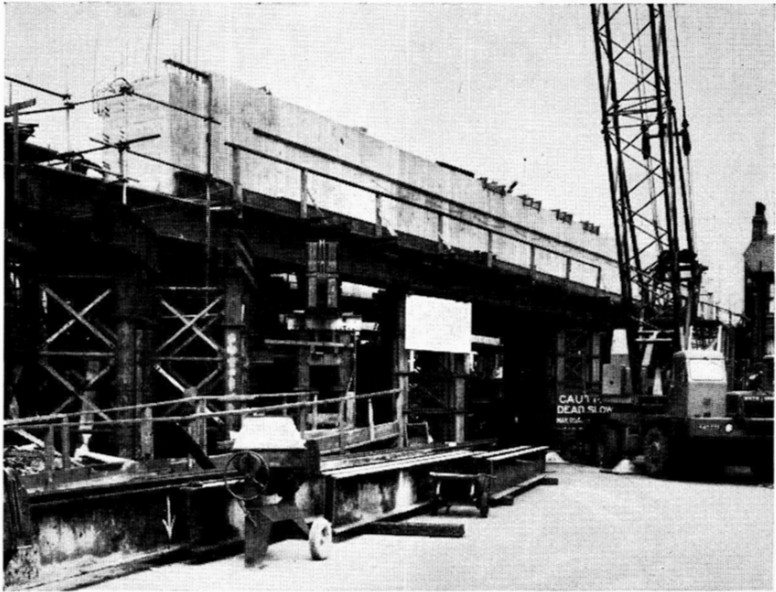


FIG. 20. STOCKPORT ROAD BRIDGE (No. 23), BEAM NEARING COMPLETION, READY FOR JACKING ON TO THE ROLLING TROLLEY

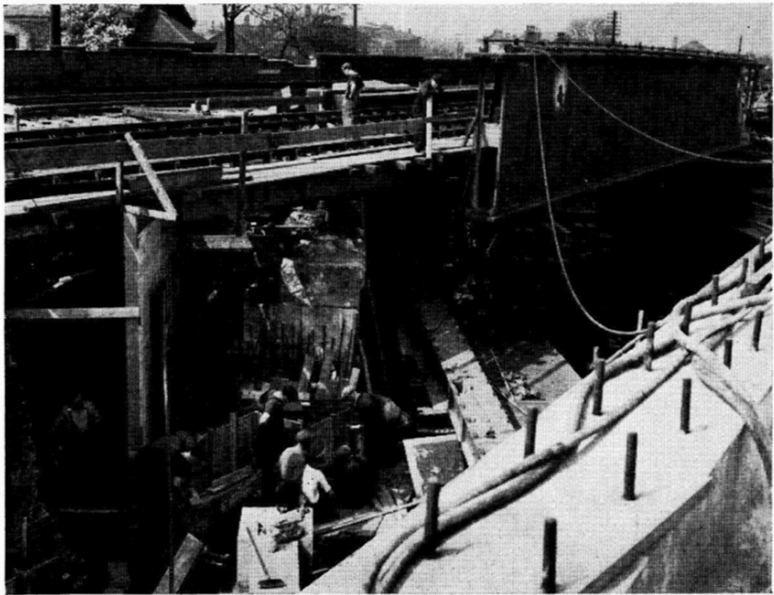


FIG. 21.—STOCKPORT ROAD BRIDGE (No. 23) SHOWING TEMPORARY SUPPORTS FOR MAIN GIRDERS AND PREPARATION FOR ABUTMENT TOPS

that during all load combinations there was no uplift at those points. It appeared from the Paper that this had been done by jacking and adjusting the reactions in such a manner that the induced load on the end bearings cancelled any uplift. Having induced the intended reactions by jacking and the use of shims, how was it intended to maintain the values of those reactions particularly the early life of the structure?

107. The particular design solution—which was an extremely ingenious one—was little different from the normal three-span beam in this connexion; and it was well known, and had been for a long time, that creep and shrinkage usually caused changes of reactions in statically indeterminate prestressed concrete structures. In the present case, longitudinal and torsional creeps were involved, and in view of the stiffness of the structure the change of reactions could be significant.

108. In most of the early continuous prestressed structures, and some being built at the present time, jacks of one kind or another were incorporated, first, to ensure that one obtained the desired reactions, as was done here. But such jacks were usually left in, because it was appreciated that, owing to creep deformations, the reactions changed. Until stability had been reached the jacks were left in so that checks could be made to obtain, eventually, a reaction/time curve which was asymptotic. But there was no mention of that in the Paper and he could not but wonder whether, having induced the required reactions, there might not be some change caused.

109. In addition, reactions could also change due to differential settlement of the supports. Could the Author state if these factors had been evaluated, whether the calculated reaction changes were significant, what the values were, and—if significant—what measures were intended for dealing with these effects?

Dr J. E. Spindel (Senior Engineering Assistant, British Railways, London Midland Region), said that two points in the design of these bridges might have general application. The first concerned the considerable reduction in the bending moment which occurred in torsionally stiff skew bridges. As a somewhat simpler illustration he could quote an isotropic slab 31 ft wide spanning a 35-ft gap. If an angle of skew of 60° doubled the span to a 70 ft skew span, the greatest bending moment under a uniformly distributed load was only 28% greater than that corresponding to the square span, i.e. it was only one-third of that corresponding to the skew span. The principal bending moments would be approximately at right angles to the abutments and there would be a redistribution of reactions. He believed that this showed that skew crossings need not be so much more expensive than right-angled ones if all relevant factors were taken into account in the design.

111. The second point concerned a limitation in the use of models for design. Three models were used for the design of Fairfield Street. The first, a piece of cardboard later improved by the addition of rubber legs, had not been described in the Paper. The second, a precision model in Araldite, was mainly used to obtain influence lines for the reactions by measuring the deflected form of the structure when one of the points of support was raised—the usual application of Clerk Maxwell's theorem. These influence lines were accurate to 1%.

112. The third was a partly reinforced, partly prestressed concrete model subjected to the scaled-down dead and live loads for the bridge. The reactions were measured directly on proving rings so that it had been possible to determine the effect of settlement of the supports. A reassuring feature during these tests was that the direction of the cracks under overload agreed with those predicted by calculation.

113. None of the three models had shown any distortion of the cross section and yet the only way load could be transferred from one web to another was by bending the top and the bottom flanges of the box.

114. To get a more accurate idea of these bending effects, a mathematical analysis had been attempted which produced 142 simultaneous equations. These, when presented to a computer, resulted in complete nonsense. It later transpired that the equations were not only very sensitive to inaccuracies in coefficients but, rather surprisingly,

also to the order in which they were solved. The same set of figures had given non-sensical answers in three different computing centres, the last of which produced sense by changing the method of solution.

115. Fig. 17 showed the results of one such calculation relating to a 120-ft span section simply supported (i.e. the centre span of the bridge). The top diagram showed transverse bending due to a sinusoidally distributed load on one web. Despite the considerable bending, the deflexions of the webs shown by the small circles on the lower diagram lay almost on a straight line, so did the three crosses showing the longitudinal stresses in the top flange. Shears in the webs, however, shown by the rectangular bars were distributed quite differently. It must be said that their distribution was more uniform under symmetrical loading.

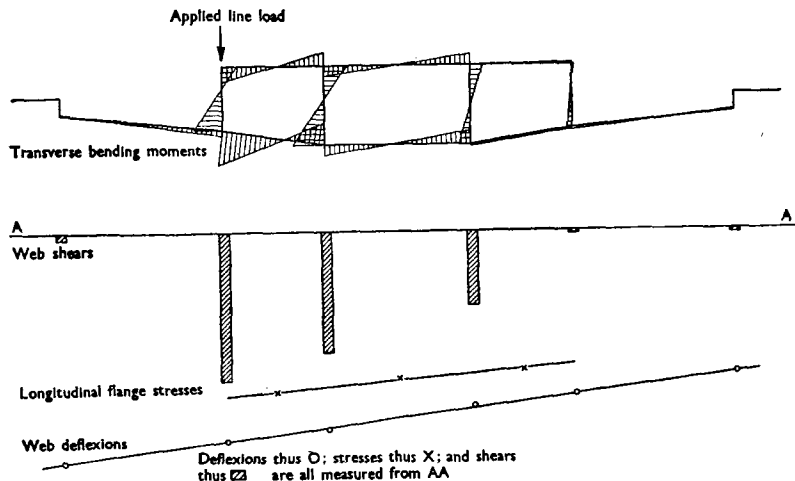


FIG 17.

116. Neither the transverse bending nor the unequal distribution of shear was apparent in any of the model tests, nor could it have been determined by any of the available techniques. It seemed, therefore, that the results of model tests had to be treated with reserve inasmuch as all features of a problem had to be studied to decide matters which might not be disclosed by the tests.

117. In conclusion, it might be said that as far as limited tests had shown, the fourth version of the bridge, the full-sized one, behaved like the other three.

Mr N. W. W. Cockcroft (Chief Bridge Engineer, Sir Bruce White, Wolfe-Barry and Partners), said that he had been particularly struck by the wonderful Fairfield Street reconstruction. It was a most ingenious solution of a difficult problem. He asked why had different systems of prestressing been used on the same job? It was usually more economical and convenient to stick to one system, although that involved compromise where several different things were being done.

119. It would be helpful to hear from the Author a brief summary of his reasons for choosing each system for its particular application.

Mr A. F. Gee (G. Maunsell and Partners), said that Mr Kingsbury had given details of the cables, ducts, and grouting at Fairfield Street but he had only touched briefly on

the details of the Stockport Road Bridge. In § 14 the Author had stated that change of direction of the prestressing cables was effected by bearing on reinforced concrete diaphragms; and Mr Kingsbury had mentioned special boxes. Could more be said on these? Were they some kind of machined steel saddles or drilled separator plates, and how did the change of direction affect these multi-wire cables?

121. In § 24 the Author said that steel sheaths were introduced near the ends of the beams, through which the stressing cables were threaded, before being tensioned and grouted. If the cables were laid in grooves in the bottom of the flanges, how were they enclosed in order to be grouted? Were two or three different methods of cable protection used?

122. Then in § 32 the Author stated that a model test had revealed that there would be difficulty in making satisfactory connexions between transverse floor members and the main longitudinal box girders. He agreed that there probably were difficulties, but having done those tests, could the Author now say just what problems arose—were they purely difficulties of detail or design problems connected with the torsion in the main girders, or something else?

123. In § 42 the Author described the 4½-in.-thick plain *in-situ* concrete joints between the precast units on the Hyde Road bridge. Was that found to be a satisfactory width for joints in a 2-ft-thick slab? Had he experienced trouble in getting the joints in? Also (although he knew the bridges had been built in the opposite order) why was not that system used at Stockport Road?

124. The Paper dealt only sketchily with the details but he had visited the site at a time when one of those beams was being jointed and he remembered the 8-in.-wide transverse diaphragms coinciding with the joints between the units so that the two were poured together. Why were not the diaphragms made part of the precast units, the units being separated by 3-in. or 4½-in. joints as in the other bridge?

125. In § 61, the losses in the main longitudinal and transverse cables were quoted as 33% and 28%. Was there any special reason for these apparently excessive losses?

126. The Fairfield Street design was a most imaginative structure but on the other hand he had been equally fascinated by Stockport Road, and he endorsed all that had been said by Mr Goldstein. He would like to know much more about the investigation into the effects of torsion and the continuity of the so-called three-span structure, and just how much was gained thereby.

127. One speaker had quoted figures for an equivalent skew slab, and these sounded reasonable, but the torsional difficulties and problems arising at Stockport Road would differ from such a slab. He wondered if it had been assumed that the vertical flexibility or elasticity of the rubber bearings would help. In other works, the supports not being entirely rigid would result in the reactions adjusting themselves as the structure crept, with the rubber bearings helping to maintain the designed equilibrium.

128. Basically, the major disappointment in the Paper was that the Author appeared to accept prestressed concrete in railway bridge construction from the railway authorities' point of view without any particular comment. It was well known that that was not a view generally found among railway authorities. For years they had avoided this material. Also, the Author had made no mention of those design problems which were unique to railway bridges and how they were overcome. Or was a blind eye turned to them?

129. In the Paper, and also in his introduction, the Author gave the impression that prestressed concrete had been accepted because steel had not then been available. He himself would like to believe that that was not so but the impression had certainly been given that if steel had been available at the time, prestressed concrete would not have been used.

130. In the past it had been suggested that the design of railway bridges in prestressed concrete was difficult and perhaps even fraught with danger. The words "vibration" and "fatigue" were breathed mysteriously whenever the subject arose. Had any serious consideration been given to either of those effects in designing the

bridges? Alternatively, could it be assumed that what might be thought rather low working stresses had been adopted as a safeguard against the unknown?

131. Here he was referring to the maximum stress of 2,000 lb/sq. in. relative to the specified minimum strength of 7,000 lb/sq. in. In fact, the specified minimum strength in the Hyde Road Bridge was 6,500 lb/sq. in. Why the difference? Incidentally, the figures quoted for the concrete at Stockport Road Bridge indicated that at least 15% of the compression tests were failures. Was there any particular reason for that, and was there any consequent action?

132. Additionally, the initial steel stresses varied a great deal between the three jobs (60.5 tons/sq. in. at Stockport Road to 75.5 tons/sq. in. at Fairfield Street). Was that, again, an attempt to allow something for the unknown elements in the design, or was the very low initial stress at Stockport Road necessary in order to meet the ultimate load requirements, since the steel content appeared to be quite low? Or again, was the final relaxed stress used as the criterion? That appeared to be just over 50 tons/sq. in. throughout.

133. Finally, could the Author give more information about the costs? Mr Gee did not know whether such information was freely available in a nationalized industry but the Author had said in § 10 that limited information was available as to the cost of prestressed concrete railway bridges, and it now appeared that he was reluctant to do anything to alleviate that unfortunate situation.

Mr J. S. Calf (Construction Assistant, New Works Office, British Railways, Manchester), describing Fig. 18* said that it illustrated an early stage in the construction of the Fairfield Street Bridge with its unusually heavy and complex temporary works necessary to bridge two lanes of heavy traffic and trolleybuses that could not be re-routed. The substructure also incorporated jacking towers to enable the structure to be lowered to take up its final shape progressively, as the prestressing was introduced.

135. Consideration had been given in the design of the framework to allow for the longitudinal movement of the concrete caused by shrinkage and elastic shortening, so as to avoid the risk of crippling the support joists.

136. Fig. 19 illustrated an advanced stage in its construction. It could be seen that the bridge was concreted in short bays to reduce shrinkage and to a pattern to load the temporary works evenly. The usual care was taken with the curing and special care was taken to ensure that the stressing wire and cables were free in the ducts after every concreting operation. That was especially difficult for the cables with buried anchorages. To avoid risk of damage, the supervisors had special instructions on the care that should be taken in vibrating the concrete.

137. The concrete was placed by monorail from a batching plant in the sidings fed by rail. It was carefully controlled and very high early concrete strengths were obtained. Work progressed round the clock to meet the completion date, and there was exceptionally good weather.

138. The end blocks were one continuous pour. Some difficulty was experienced in placing the concrete because of the high density of reinforcement and stressing cables. Strict attention was paid to the vibration of the concrete using various types of vibrator. Honeycombing could not be allowed with the high stresses in those blocks. The majority of the distribution plates were cast in.

139. Fig. 20 showed one of the Bridge 23 beams nearing completion in readiness to be rolled into position during a rail possession of 30 hours. As described, the beam had been assembled in sections, diaphragms cast and the whole stressed together.

140. The 65-ton crane had not the capacity to place direct more than one quarter of the units. It was necessary, therefore, to build into the steelwork staging a rolling path for the specially designed trolleys that moved and positioned the 35-ton blocks, once the crane had lifted them to platform height from the low-loaders.

* Figs 18-21 are photographs and are placed between pp. 320-321.

141. The programme of lifting and positioning 6 units during each night's rail possession was met by this method. Once the beam was stressed, 200-ton jacks fitted with gauges were used to lift the beam clear of the platform when the staging could be removed and the beam lowered on to the assembled rolling trolleys. It was found when jacking each end independently that a rapid transfer of load could and did take place, and without gauges to warn the operators, the jacks could be loaded beyond their capacity. Coupled jacks were not used but could have been an advantage.

142. Care was taken that following packs kept pace with the jacking or lowering. To increase the number of military trestling columns to take care of the concentrated load at the jacking towers, special struts were designed to allow for the columns to be located at 2 ft 6 in. centres instead of the standard distance of 5 ft. 40 tons was the maximum design load permitted on any column.

143. Fig. 21 showed the work to the abutments progressing in readiness to receive the beams shown being cast alongside simultaneously. Meanwhile, the existing bridge was supported from the temporary works. Prefabricated standard waybeams bridged the gap. The burners cutting up the old, well-maintained wrought-iron structure had to be protected against lead poisoning, which became serious.

144. Fig. 14 in the Paper showed the rolling-in operation of Bridge No. 30. The permanent way had been removed from the centre portion of the bridge, the structure having been dismantled and removed. The tracks had been broken on the span moved in earlier, in readiness to be moved further into the bridge; and the second span (shown on the right) was ready to be rolled in to take up the position of the first span. That operation had been carried out three times to complete the bridge of three beams carrying the six tracks.

145. The centre rolling path was visible alongside the centre pier supported on military trestles. The end rolling paths were positioned on the abutments behind the continuous bearing—an arrangement which, in Mr Calf's view, was not desirable since it was inaccessible and would entail a major operation should anything go wrong with the rolling path. It was made necessary, however, by a building which projected in front of the abutment. The spacer plates for the steel balls were absolutely essential in heavy rolling.

146. There had been some discussion as to whether rolling paths should be given a fall. He suggested that a level bed was preferable.

147. All the beams had been winched in by two 60-ton mining winches which proved ideal, each being operated individually on a system of light signals given from a central point. Back anchorages had been provided as a precaution.

Mr Donovan H. Lee (Consulting Engineer), said it seemed that everybody could be right about the life of prestressed concrete and its deterioration; but as Mr Berridge had said, and the Author, apparently, had assumed, no-one knew of any reason (apart from unfavourable atmospheric causes) for the deterioration of prestressed concrete.

149. Someone had expressed doubts about the effects of creep being finished within 2 years, but there was little creep then, and these things were understood. The useful life of such a bridge due to unfavourable atmospheric conditions could not be closely foretold but it was known, for example, that the corrosion rate of exposed steel in places like Sheffield was about seven times as great as at Calshot, in Southampton Water. That atmospheric conditions had some effect on concrete was of course also known. Various chemicals in the atmosphere, including sulphur and perhaps also fluorspar and sometimes frost did damage the surface of concrete, possibly more than proportionately with the porosity of the concrete. High-grade concrete accordingly was much more resistant than the concrete of high water/cement ratio that was used for some of the early concrete structures and (regrettably) occasionally also more recently.

150. If the prestressed concrete bridge was built away from a damp polluted atmosphere and possible mechanical damage such as wear or abrasion from sandstorms, it should certainly last for 150 years and perhaps as long as some of the Roman structures

still in existence and about 2,000 years old. However, in Manchester he would be inclined to give surface protection. Although not sure of its useful life he had used silicone surface treatment on exposed prestressed concrete of a hangar at Bombay, also at Sheffield with an asbestos-cement roof and elsewhere on concrete surfaces merely to shed the water and reduce discolouration by dirt; in industrial areas he felt it was worth the small extra cost.

Mr T. N. W. Akroyd (Chief Engineer, Constructional Services Limited), said that prestressed concrete was subject to attack by atmospheric oxides and carbon dioxide which dissolved in soft water.

152. His recollection of Manchester was that the only things there which were about 80 or 90 years old and which should have had a high resistance were sandstone lintels on old buildings. Those were composed of quartz grains usually cemented with silica—both highly resistant materials. In concrete, however, there was free lime which was not so resistant. It might well happen that carbon dioxide dissolved in the Manchester rainwater would attack the surface.

153. Having reviewed buildings up and down the country he had come to the conclusion that $\frac{1}{2}$ in. of cover was penetrated in 20 years, and roughly $\frac{3}{4}$ in. in 40 years. When there was that amount of cover over the reinforcement there was corrosion of the reinforcement and falling off of the concrete. That could happen only when the free lime was carbonized by reaction with atmospheric pollution.

154. With prestressed concrete bridges it might happen that after a long time, perhaps something in excess of 80 years, the surface would be attacked to a depth of about 1 in., which would make no difference. That was the beauty of prestressed concrete—there would never be such small amounts of cover as were found in reinforced concrete. After such a period, however, with further attack and the concrete becoming soft, a maintenance problem would arise. He did not believe a life of 150 years could be claimed.

155. In considering the life of a concrete bridge one must consider two things, first the maintenance of the concrete and secondly the protection of the steel. Concrete in a polluted atmosphere was known to be subject to corrosion by acids dissolved in the rainwater, of which the most important were due to carbon dioxide and sulphur. Sulphur, as weak sulphuric acid, could cause severe damage but whilst these effects must cause expenditure on maintenance they would not lessen the life of the bridge in the same way as could occur when the steel in the concrete was corroded.

156. The protection of the steel in a concrete bridge depended upon the quality of the concrete and the amount of cover because these were related directly to the maintenance, around the steel, of an alkaline layer with a *pH* value of about 12. The corrosion of steel at ordinary temperatures was an electro-chemical process and depended upon the maintenance of a low electro-potential. With the passage of time, the concrete became permeated by moisture carrying carbon dioxide. The carbon dioxide converted the free lime in the presence of moisture to calcium carbonate. This led to a gradual reduction in the *pH* value, the electro-chemical potential then increased and conditions were ripe for corrosion.

Mr H. E. Jones (Chief Design Engineer, Leonard Fairclough Ltd), said the Author had stated that the average strength of the concrete was about 9,000 lb/sq. in. at 28 days. He himself had gone to Fairfield Street and tested the concrete with a Schmidt hammer. He had examined the two main columns made of the same concrete as the prestressed concrete deck and the stress had been between 10,500 and 11,500 lb/sq. in.—which showed a definite increase in strength.

158. The grout used for the cables was specially designed for the job and was very strong—about 0.38 water/cement ratio. Having one cube left over he had tested it and found a crushing strength of 10,870 lb/sq. in.

Mr David Smollett (Partner, Smollett & Magasiner, Consulting Engineers), said that some years ago he been employed on the design of a series of overbridges on the same section of railway line as that spanned by the three remarkable bridges mentioned in the Paper.

160. First, the expected life of these bridges had been put as high as 150 years. The life of the rubber bearings however would be much less than this, perhaps as little as 20 years, and provision would have to be made for this. Perhaps the Author would deal with that point.

161. Secondly, it was interesting to hear that the railways were now willing to accept the design of a skew slab as a skew slab. One of the bridges he had been engaged on presented a considerable skew angle, and he had prepared a design based on the relaxation of a grid of 32 points, treating the slab as isotropic. This had led to a considerable reduction both in bending moments and required depth, somewhat of the order of magnitude mentioned by Dr Spindel earlier. When he had presented this to the railway authorities however, he had been told in effect to take it away and redesign it as a series of simply supported beams. He was glad that the more rational method of design was now being adopted.

162. Thirdly, silicone treatment had been specified for the bridges mentioned, and, he thought, applied to prevent the deterioration of the surface. He had since been told, however, that under some circumstances the use of this substance would lead to the surface concrete being pulled off by the film of silicone paint, and perhaps the Author would say what measures, if any, were taken in the treatment of concrete surfaces?

The following contribution was received in writing:

Mr J. D. West (Bridges Assistant to the Chief Civil Engineer, Eastern Region, British Railways), wrote that Mr Lloyd Owen had inaccurately stated that an electrified line on a voltage of 25 KV was first opened on the London Midland Region of British Railways. This voltage had first been introduced experimentally when the Colchester to Clacton Electrification Scheme (Eastern Region, British Railways) was opened to the public on 13 April, 1959.

164. Mr Berridge had expressed strongly his gratification that no concrete in tension was used in the design of the three bridges of the Paper. Though he had no criticism on this aspect to offer on these three bridges he felt that these remarks might be interpreted as covering a more general field.

165. Concrete in tension, or "partially prestressed concrete" as it was perhaps better known, had been well tried and had its place in bridge design. Many bridges in Britain, rebuilt in connexion with electrification or in the normal course of maintenance had been satisfactorily constructed on this principle and described in institution journals. Generally the tensile stresses were momentary, resulting from conditions of maximum live loading, and normally the structure was under compression.

The Author, in reply, recalled that Mr Butland had asked whether in the light of the lessons learned he would alter his procedure if he were to start again on any of the three bridges. Under similar conditions he could not think of any alternative. If the conditions were entirely different, if, for example, steel were immediately available, he believed that at least for Bridges Nos 23 and 30, he would look closer into the possibilities of using steel. But that aspect had been fairly well probed for No. 23, and it had been found that there was no difference in the estimated cost, in fact if anything there was a slight advantage to prestressed concrete. Probably the only differences in the three bridges would be matters of detail. For Fairfield Street Bridge he could not think of any other satisfactory solution than the prestressed concrete bridge.

167. Mr Berridge had said that he did not doubt that steel would be cheaper. The Author believed the answer he had just given to Mr Butland's question met that point for Bridge No. 23. With regard to No. 30, a steel design was not strictly suitable

for the type of construction adopted—a continuous isotropic skew slab. Bearing all matters in mind from the point of view of railway working—the difficulties to be encountered in erection and the fact that the use of the prestressed concrete slab eliminated encroachments on clearances, which was an important factor in railway work—prestressed concrete would have been adopted in any case.

168. With regard to the question of life and maintenance of prestressed concrete bridges, he would not dispute that the life might well be 150 years. As far as he could see the life would be almost indefinite. Whether there would be any need for maintenance work was debatable. It had been pointed out that in an atmosphere such as that at Manchester there might be concrete surface deterioration, but it would seem possible to deal simply with that when it arose. The value of applying some surface-hardening treatment now was doubtful.

169. With regard to the question of the use of a steel plate between rubber and concrete; he felt it preferable to have such a plate in similar circumstances. At Bridge No. 30 they had a continuous plate for the full length of the skew bearing, quite a long one; and to ensure that the concrete would have been properly bedded without the plate would be asking rather too much, although there were difficulties in ensuring that even the steel plate was in the proper plane. It would have been much more difficult with concrete alone.

170. Mr Cockcroft had asked why different systems of prestressing had been used in the Fairfield Street Bridge. There were a number of reasons. Macalloy bars were much more positive, with short lengths of about 11 ft, than any other system of prestressing. They would not have been convenient in the main tendons, and since there were difficulties in providing anchorages, large diameter strand was used for the principal prestress and Magnel cables for the transverse prestress. It was mainly a question of providing sufficient space for anchorage of the tendons.

171. Mr Gee had raised a number of interesting questions demanding a written reply. Amongst these he had suggested that prestressed concrete appeared to have been accepted by the railway authorities without question; but prestressed concrete was no stranger to British Railways. It had been very widely used for bridgework by them since 1946. What was believed to be the first main line underbridge in the world in prestressed concrete had been built by British Railways in 1946. It was still standing, in an atmosphere similar to that of Manchester and no deterioration had yet been noted. Railway engineers were, therefore, conditioned to the use of prestressed concrete as an alternative to steel.

172. The question of whether or not fatigue would be a factor to be reckoned with in prestressed concrete railway bridges had been dealt with by carrying out full-scale dynamic tests at Liège University as long ago as 1951. Several full size post-tensioned slabs and pretensioned beams were made and transported to Liège, where they were subjected to a programme of rigorous tests, one outcome of which was to show that confidence could be placed in prestressed concrete, so far as fatigue was concerned.

173. Several people had mentioned the maintenance of concrete and he had been pleased to learn that Mr Akroyd would have full confidence in using prestressed concrete because of the increase in cover that could be and often was obtained. That, together with the fact that it could be made to be always in compression, was one of the main reasons why it had been decided to use prestressed concrete on British Railways—because it would reduce maintenance costs.

174. Mr Smollett had referred to the life of rubber bearings. The generally accepted figure was 25 years but he believed this had been deduced from accelerated ageing tests which had been carried out to an equivalent life of 25 years. That did not mean that the bearings would not, in fact, have a longer life than that. They might well do so. But wherever they had been used provision for their renewal had been made, since clearly they would not last as long as the concrete.

175. In the Author's written reply he said that Mr Goldstein's question on the rather high creep value adopted for the Fairfield Street Bridge was appreciated. At this bridge,

because of torsional effects, the net deflexion under dead load and prestress was downwards and would be increased by shrinkage and creep. Rather high values were, therefore, allowed for these, particularly for creep, to ensure that the bridge would not appear to sag.

176. The model test for Bridge No. 23 was made on a solid rectangular piece of Perspex, so proportioned as to have the same relationship of torsional to flexural rigidity as had been calculated for the box section. Loads were applied on the span and the deflexions of the outer bearings in relation to those of the inner bearings were measured. Loads were also applied at the ends and similar measurements taken. The results confirmed the theoretical calculations for the outer bearing reactions. The theory for thin-walled hollow members was used for calculating the torsion stresses, but warping stresses were neglected because it was considered they would not be of great significance at critical points. The torsion stress mainly affected the web shears near the bearings.

177. With regard to changes that might take place in the future and which might be expected to have an adverse effect on the strength of the box beam, it was considered that the most important would be differential settlement of the bearings and change in the deflected shape of the beam due to shrinkage and creep. These were checked and it was found that for a change of the order of $\frac{1}{4}$ in. the reaction at the inner bearing varied a negligible amount, about 20–30 tons. It would be appreciated that any long-term change in the dead load reactions would be evident from the appearance of the rubber bearings and it was not expected that there would be any significant settlement of the abutments. The deflexion at the inner bearings under live load was, of course, of short duration and was not affected by shrinkage and creep.

178. It should perhaps be made clear that the jacking operation referred to in the Paper was not so much to induce a reaction into a continuous girder as to lift the girder at the outer bearings so that the inner bearing reactions would be almost negligible under dead load.

179. Mr Cockcroft had asked why different systems of prestressing had been used in the Fairfield Street bridge. An answer in general terms had already been given, but some further detail might be of interest. The main prestress consisting of 1 $\frac{1}{4}$ -in. diameter strands was chosen because this system gave the minimum number of individual tendons which could be anchored in a confined space without requiring too many hollow ducts near the anchorages. The transverse prestress called for anchorages that could be buried conveniently in the surrounding concrete. At the time, this requirement could not be met by large diameter strand and the choice, therefore, fell on special Magnel cables which were found to be suitable. Freyssinet cables were used for the capping prestress because they required the least duct space near the anchorages and were the only ones having concrete anchors for burying in concrete, a desirable factor at these locations. Macalloy bars were used in the webs and diaphragms because they provided the only simple means of prestressing over an extremely short length without anchorage slip.

180. The special boxes in the diaphragms of Bridge No. 23, referred to by Mr Gee, were sheet steel *gaines* in which were placed ordinary Magnel cable separators. No special effect on the cables at changes of direction was noted. Magnel cables, of course, changed direction only at spacer grilles.

181. The cables in this bridge were protected where they lay in grooves by cement mortar, and elsewhere by enclosing in sheet steel *gaines* which were afterwards grouted.

182. The difficulties encountered in the model test for the first proposed design for Bridge No. 30 (Hyde Road) chiefly arose from the skew. It would be appreciated that because the skew would cause the two ends of a transverse floor slab to deflect by different amounts there would be rotation at their bearings on the main box girders. The resistance offered to this rotation by practicable connexions, such as those tried, so increased the bending moments in the reduced section at the ends of the floor members that ordinary reinforcement was seriously overstressed in bond and at the hooked

anchorages. A more satisfactory joint could be produced by using steel plates to which could be welded reinforcing bars, but this, apart from being expensive, had serious defects from the maintenance points of view. Appreciable cracks in the concrete were noted in the test under simulated working conditions.

183. No unexpected difficulty was encountered in making the 4½-in. wide joints between the solid transverse units at Bridge No. 30. The units for Bridge No. 23 were hollow boxes and the prestressing cables were inside the boxes. Some means of deflecting the cables to the required sweep was needed and the solution adopted was to cast 8-in. wide diaphragms between the units, wide enough to permit the fixing of reinforcement and the efficient placing of concrete. It was considered easier to do this than to precast each diaphragm as an integral part of one of the units, as suggested by Mr Gee.

184. The losses in prestress quoted for Fairfield Street bridge included allowances for friction in the heavily curved cables.

185. The advantage in the Stockport Road (No. 23) design by exploiting the continuity effects was considerable. The span was effectively reduced from 123 ft (skew span) to 107 ft, thereby permitting a shallower beam than would have been required for the longer span.

186. With regard to the concrete working stresses, the higher quality concrete in Bridge No. 23, compared with that called for in Bridge No. 30, was specified because during rolling-in, the maximum compressive stress was calculated to be of the order of 2,400 lb/sq. in. No concrete test cube was under specified strength.

187. The initial steel stresses used were adopted after very careful consideration of all factors, and were thought to be reasonable, having regard to an adopted final relaxed stress of about 50 tons/sq. in. The large diameter strands in Fairfield Street bridge were taken to a much higher initial stress than the 0.276 in. dia. wires, because it was known that the stress would be reduced both by anchorage slip and creep within a very short time. This high initial stress was tolerated because the strands were composed of a number of thin wires having a greater tensile strength than the 0.276 in. diameter wire.

188. Limited information on costs of prestressed concrete railway underbridges was available at the time of design. Although many prestressed concrete bridges had been built by British Railways in the preceding twelve years, both under and over the line, and of varying types, none had exceeded about 70 ft in span. Furthermore, they had been composed of a number of individual longitudinal beams that could be placed quickly in their final positions by railway cranes. The cost of these were known, but they could not be taken as criteria in estimating the cost of large span underbridges of unusual design that had to be erected under very difficult conditions.

189. The Author assured Mr Gee that the apparent reluctance to quote costs was not connected with the fact that these bridges were constructed by a nationalized industry, but merely because of the fear of quoting figures which, without a lengthy explanation, could be misleading. It might be said briefly that in railway underbridge reconstructions the cost of track work, demolition of the old structure and erection of the new, frequently formed the bulk of the costs and in particularly difficult locations they could be proportionately so heavy that any difference there might be between steelwork and prestressed concrete before being placed in the line, receded into insignificance.

190. No silicone treatment of the concrete surfaces was specified for any of the bridges, as referred to by Mr Smollett, nor was any such treatment given.