Some special applications of prestressed concrete to civil engineering structures

by

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AUTHOR'S INTRODUCTION

Mr Walley, in presenting his Paper, said that he had been very conscious of the fact that the impression could be created that prestressed concrete might be regarded as the solution of problems of civil engineering structures in general, but it had to be emphasized that the structures chosen for the Paper were only a few of a great many such projects for which the Ministry of Public Building and Works were responsible.

64. One common thread might perhaps be found to be woven into the pattern of jobs presented in the Paper, and that was of designing for moving or dynamic load conditions. The single exception might be the case of the test floor for the Building Research Station, but even in that case fatigue loading would be quite proper if it was desired to carry out such tests.

65. Since the prime purpose of the Paper was to indicate why prestressed concrete was the chosen solution for the various problems that presented themselves, in his introduction he contrasted the solutions presented in the Paper with solutions which had been used earlier for similar but often subtly different facilities. He demonstrated this from a large number of slides illustrating both the projects described in the Paper and similar projects using other forms of construction.

Dr S. C. C. Bate (Head of Structural Engineering Division, Building Research Station, Watford) thanked Mr Walley for a most interesting Paper describing some unusual prestressed concrete structures. As the Author had said, four out of five of his structures were likely to be subjected to some form of dynamic loading in service, and it might therefore be concluded that he thought prestressed concrete was particularly suited for dynamic or repeated loading. How far had Mr Walley come to his conclusion from the results of research?

67. In particular, he referred to work on research in connexion with the design of the rocket engine test stand. Research workers were always glad to see the results of their work being introduced directly into design, and Dr Bate asked Mr Walley whether, in this case, the research effort was repaid by the improvements achieved in the structure?

68. The Author also referred to tests in dealing with the choice of prestressed concrete for the R.A.E. laboratory at Farnborough. He mentioned that the loading on the floor for repeated loading was 70% of that for static loading. Was this because he had had some doubts of the prestressed concrete structure; was it a limitation imposed by the testing equipment; or was there any other reason?

69. Details of the cable extensions for this structure were given in Table 2. Maximum, minimum and average extensions were set out against the theoretical extension, and Dr Bate had noticed that some of these exceeded the required extension by 10% or more. As he was sure Mr Walley was aware, the present Code of Practice allowed tendons to be stressed up to 70% of the tensile strength, with the implication that this could be raised to 77%. There was also a clause which allowed 2½% of the wires in the cables to fracture, provided that the total prestressing force was not

reduced. As a result of his experience on these and other structures, did Mr Walley feel that the present requirements of C.P. 115 were adequate and practicable? What were his views on the suggestion that the initial permissible prestress for the tendons should be 85% of the tensile strength in the future revision of the code?

70. The new laboratory at the Building Research Station was of special interest to Dr Bate since it provided the environment for structural engineering research at the Station for many years ahead. The new laboratory was designed for research into the behaviour of combinations of components in multi-storey, multi-bay structures, whether of framed, load-bearing wall or other construction. It would provide for the testing to collapse of full-scale structures in an environment of constant temperature and humidity with consequent advantages in measuring strains.

71. It might be of interest to mention that the specification for the new laboratory had been prepared seven years previously, and had been agreed with the Ministry of Public Building and Works one year later. Since then, the specifications for loadings which Mr Walley had set out in his Paper had remained virtually unchanged. An additional loading requirement was the provision for horizontal loading for a wind load of up to 120 lb/sq. ft on the largest type of structure which could be accommodated. As the new structure had not yet been used, he could not say how far the specification met future requirements for testing, but for work already planned it was clear that it should not be smaller. It seemed that the maximum limits set on the loading conditions were likely to meet all requirements for the immediate future.

Mr A. J. Harris (Harris & Sutherland) felt that the reaction of any designer to the Paper would be one of envy of Mr Walley in being able to participate in some exceedingly novel design problems apparently at a sufficiently early stage to affect the basic concept of the structure. The Author had been in a position to indicate the possibilities to his Client and could bring forward exactly the right material. A second feature of the Paper was that it described uses of prestressed concrete in which certain inherent and rather unusual characteristics of the material were employed to full effect.

73. Two of the structures had explosive loadings, something which was exceedingly difficult to represent in static terms. The Author could add very much to the value of the Paper if he could enlarge on this aspect. With explosive loadings there were two elements: the explosion itself, and the response of the structure. With a different structural material the effect of an explosion could be markedly different. For instance did Mr Walley, in his calculations of structural adequacy, take into account any of the behaviour of prestressed concrete in the cracked phase? With a load of very short duration, this could be of considerable interest, and could have a great bearing on the response of the structure to the explosion.

74. Secondly, referring to the testing tunnel, it would seem that the effects of explosion would be more severe in the transverse than in the longitudinal direction. Had the Author considered a transverse prestress instead of reinforcement?

75. Lastly, the Author had shown some *frightening* pictures of secondary mild steel in the very high stress areas beneath the hinges. Had he given any thought to the use of high tensile bolts in that area? This was becoming an accepted means of prestressing and was available for quite small volumes.

Mr J. N. Lowe (Senior Partner, Lowe & Rodin) thought that the Paper and the presentation had brought out more than anything else the utter simplicity of the solutions. He had two basic questions to ask. First of all, it seemed that most of the examples were test jobs, a field in which hitherto it had been assumed that steel or metal held sway. Was it the case that in all instances movement and the restriction of movement were the main criteria for the design? Were the limits stated in most examples those of movement, or had other limiting states to be considered as well?

77. In a Paper concerned so much with measurement, perhaps Mr Walley could

answer some questions on concrete properties. In § 19 there was a fairly casual measurement of E of 3×10^6 but any E of between 1.5 and 6.0×10^6 could be very reasonable. There were a number of measurements in Tables 3 and 4 in which the Author gave the measurements on the job in lb/sq. in. Were these really measurements of stress or conversions from strain *via* an assumed E ? This was particularly important because, in Table 4, the expected or theoretical calculated stress in the basement slab might have been 400 and 1000 lb/sq. in., or, in the ground floor slab, 360 and 1200 lb/sq. in. The figures were such as to make one assume that there was much more restraint in the basement slab than in the ground floor, though he himself would have expected very little friction with the sand support to the bottom slab. Would Mr Walley say whether or not the Young's modulus in the basement slab might not have been markedly different from that of the ground floor slab? Even the possibility of its being wet underneath could have modified the E .

Mr L. R. Creasy (Ministry of Public Building and Works) said that the five subjects included in the Paper formed a neat group of unusual structures that were worthy of note for the function they served as well as for the method of construction. It was a useful reminder of the service which the civil engineer provided to the technological activities of the community, which affected efficiency, productivity, and safety over such a wide field of interest. The cost of each of the test frames, galleries and tunnels was not less than a £½ million and this was for the bare essentials of structural frame and cladding. Perhaps it offered some explanation of the high cost of research, and a reminder, if that were necessary, of the importance of seeing that the facilities were fully and efficiently utilized!

79. The Paper also provided a valuable comment on the changing attitude to prestressed concrete, especially when compared with the Author's report of only ten years previously. The latter included a number of very simple structures for single-storey frame of beam-and-post type of construction. The structures had been of very simple form, but the discussion had been very deeply concerned with the complexities of design and construction in a relatively new medium.

80. In the present Paper, all the structures described were of very unusual form and were developed for a function of considerable complexity. The present commentary on the Paper might be comparatively simple and this seemed to imply that the technical problems inherent in the design and construction of prestressed concrete work had now been mastered. In the short period which had elapsed, this was a remarkable achievement.

81. Nevertheless, one of the basic problems that seemed present in all the examples chosen was that of how to ensure that the tendons achieved their full tension and, perhaps of more importance, how to ensure a corresponding deformation in the concrete. He noted with considerable interest the neatly demonstrated value of flapjacks in dealing with this problem when the tendons were very long. Perhaps Mr Walley would comment on that.

82. Mr Creasy said that he had also tried to deduce from the examples described in the Paper basic rules to indicate when prestressed concrete became an appropriate solution to present day design problems. First, prestressed concrete provided a neat solution to the problem of dealing with reversals of load and of carrying large loads with members of slender proportions. Second, it seemed that prestressing was justified when it simplified the design of awkwardly shaped members. Thirdly, many of the structures shown indicated the manner in which prestressing tendons provided a very simple way of fixing awkward cantilevers to walls and other vertical members. Finally, more than one example referred to the use of prestressing to avoid cracking and weeping in a water-retaining or water-excluding structure. This seemed to pose another question as to whether the success in this context might be due to the high quality of workmanship and the strength of the concrete, which provided fundamental insurance against the defects of poor workmanship. This implied that a similar

success would be achieved with normal reinforcement with equal quality of concrete and workmanship.

83. Perhaps the most valuable characteristic to be found in the Paper was the facility with which other forms of construction, such as steel and reinforced concrete, had been mixed with prestressed concrete. These were combined in one structure and often in one member of one structure. It would be useful to have information on the circumstance and economics which determined these decisions.

Dr R. E. Rowe (Cement and Concrete Association) said that Mr Walley had raised a number of interesting problems on which a limited amount of information was given; some questions had therefore to be expected.

85. First, referring to the rocket testing station, the Author had mentioned in § 6 that it was known that both steel and prestressed concrete were unaffected by low temperatures, but Dr Rowe had been unable to find many references to the data. That being so, would Mr Walley elaborate a little on this item of research?

86. The second question concerned the explosion gallery. There were some very interesting data from the strains recorded on steel due to daily and annual changes of temperature. Since Mr Walley said that the data were recorded under experimental conditions, what was the finding when the explosions took place? Did the calculations performed on the data confirm that the pressures used in design were attained in practice? This was a question of loading, and it would be very interesting to find out what actually happened, as compared with what the designer was asked to assume would happen.

87. The next point concerned what might be called the very simplest prestressed structure: the hinge which supported the prestressed beams at the R.A.E. at Farnborough. Mr Walley had mentioned a design stress of 14 000 lb/sq. in. in the throat. Fig. 20 showed test specimens in which the stress was in excess of that figure in hinges very similar to those used by Mr Walley.

FIG. 20

88. Speaking rather facetiously, he thought that the Author was rather conservative in using 14 000 lb/sq. in., but he was delighted to know that an engineer had applied the results of his research in practice before the detailed paper on the research had been written.

89. Dr Rowe then referred to the structures at the R.A.E. and the Building Research Station. Mr Walley had said that at the former there were special problems concerned with thermal loading of the test structure. What sort of stresses did the thermal loading create in the prestressed structure, and what were the types of stresses which would arise in the laboratory at the Building Research Station where a controlled environment was provided?

Mr R. Cameron (Ministry of Public Building and Works) said that he was concerned with supervision, from the Ministry's point of view, for most of the duration of the construction of the tunnel at Buxton. Although this was not a very complex structure, each individual 25 ft long bay needed considerable supervision.

91. For example, the main steel was $1\frac{1}{4}$ in. in diameter, at about $4\frac{1}{2}$ in. centres, both faces, and, with the steel coming up from the bottom and crossing over, very little room was left for the concrete. There were 13 ducts for the tendons which had to be absolutely straight for 1200 ft, as otherwise it would have been impossible to stress them. In addition, there were considerable numbers of pipe clusters through the concrete which had to be very accurately placed. There were also various facilities for inspection. Further, a B.R.C. fabric of about 6 in. mesh containing Pyrotex cables was placed throughout the inside of the face of the tunnel, and this had not to be damaged in any way. There were also 10 000 cemented-in sockets which had to be fixed to the inside of the shutter in order eventually to bolt the gallery arches.

92. Considering that all this had had to be done in the open, 1200 ft above sea level, in fairly violent weather conditions, he wondered whether it was fair on the Contractor to ask for such accuracy. He also wondered whether the reason why a corresponding structure in steel would have been more expensive was partly because it would not have been possible to get engineering craftsmen to work in such conditions unless the whole structure were covered in. Some of the structure at Farnborough had been covered, but the expense of covering the tunnel structure in the conditions at Buxton, in the high winds common there, would have been considerable.

93. The Contractor had had to lay rails at each side of the tunnel for a gantry to support the formwork and rails inside the tunnel. The rails had had to be concreted into position within $\frac{1}{8}$ in., and the soffit shutter was then supported on a trolley running on the rails. All concrete surfaces had to be smooth to facilitate cleaning. An interesting point was that for the bulk of the concrete, crushed limestone and sand from the biggest quarry face in Europe had been used.

Mr D. H. Little (Walter C. Andrews & Partners) thought that the most important theme of the Paper was that for all the structures mentioned prestressed concrete had been chosen after a good deal of consideration had been given to other materials. Mr Walley was recognized internationally as an authority on prestressed concrete, and Mr Little wondered if he had been completely objective. It was extremely difficult to decide what was the best way of building a structure, and very difficult to eliminate personal feelings entirely. His own view was that while prestressed concrete was not necessarily the most expensive, there could be cheaper materials, though they might not be better.

95. Mr Walley had referred to a pressure of 14 000 lb/sq. in. bearing on the concrete hinges, while Dr Rowe had shown an example going up to 24 000 lb/sq. in. What were the cubic strengths of the concrete, and was the explanation of the high stresses the fact that these were operating over only a very small area of the mass? He was prompted to ask because of experience with a jetty built in Scotland the

previous year. This was on steel piles of 70 sq. in. cross-sectional area bearing on rock. The design load on the drawings was 200 tons, which meant that they were actually designed for a stress of 400 tons/sq. ft on the rock. In places the rock dipped at a sharp angle, so the piles did not all bear evenly on it. Some skidded off so badly that they had to be withdrawn, and were found to have buckled ends, indicating that the steel had been stressed to 16–18 tons/sq. in., with a corresponding rock stress in excess of 2000 tons/sq. ft. Accordingly, two piles were each test-loaded to 220 tons, resulting in a rock stress probably in the region of 1200 tons/sq. ft, or nearly 20 000 lb/sq. in. When the test loads were removed, recovery was almost 100% complete, suggesting that small portions of large masses might safely be subjected to very high local stresses.

Mr R. W. Pearson (Ministry of Public Building and Works) said that he had been involved in the design of a test floor for the new Road Research Station at Crowthorne. Although similar to that at Watford, it was designed independently from first principles, and had some interesting points of difference.

97. Mr Walley had mentioned the Crowthorne floor, indicating that it was slightly bigger and had a slightly heavier loading than the B.R.S. floor. It was, in fact, 100 ft long $\times$ 55 ft wide. The jack loads were 45 tons maximum, at the same 2 ft 6 in. centres.

98. He noted that whereas the B.R.S. floor had 2 ft thick slabs top and bottom, with 16 in. thick webs, the Road Research floor had a 20 in. thick top slab, a bottom slab 16 in. thick, 16 in. thick webs, and the same overall depth of 12 ft. The theory behind his own design had been that the smaller the cross-sectional area in prestressed concrete the less prestressing force was required to achieve a certain prestress, and that this was an economy well worth making.

99. Another point of interest on the Crowthorne site was the risk, which could not be evaluated, of finding water in the ground. Under full test load the floor would be lifted away from the ground in the centre of the span, the structure transmitting load to the ground mainly at the ends of the span. Under this condition the dead load of the floor gave a very useful reduction in the design moment. Water pressure from underneath would, however, largely destroy this and lead to a heavier design. A series of drains was therefore laid under the floor leading to sumps, so that, if found necessary, pumps could be used to keep water down during any time of maximum test loading. As the ground at the B.R.S. was clay, in which one might expect water to collect, had the same problem arisen?

Mr R. B. Leyland (Messrs Lowe & Rodin) pointed out that an item of concern in the explosion tunnel was friction on the sliding layer, which he believed consisted of two layers of Polythene over 2 in. of sand. He had been associated with a similar structure some years earlier in India. This was a prestressed pipe of 20 ft diameter and a total length of about 6000 ft. The element was split into 360 ft lengths and friction was overcome by flat jacks between the sections and a bituminous sliding layer about $\frac{1}{4}$ in. thick consisting of a mixture of bitumen and rounded sand.

101. First, the foundation was trowelled to a tolerance of $\pm \frac{1}{32}$ in. in 36 in. squares. The bitumen layer was then applied to 2 ft square precast slabs in order to overcome the difficulty of handling bitumen in the high temperatures in India. The slabs were then overturned so that the bitumen lay on the prepared foundation of the slab, leaving a smooth, hard working surface. To establish exactly the friction to be overcome, one 360 ft block was jacked against a succession of blocks, and it was found in each case that the friction, which took 1–2 days to develop, gave a coefficient between 0.11 and 0.14, a factor which seemed to have been considerably below that achieved with the sand and Polythene layers. Had Mr Walley considered a prepared bitumen layer as the sliding layer?

Mr W. G. Pullan (Ministry of Public Building and Works) said that as his admiration for Mr Walley's subjects and his congratulations on the Paper were very sincere, he hoped that his one comment would not sound like carping criticism.

103. He asked if there had perhaps been a design error in specifying the wrong concrete for the reinforced concrete job? He himself had made such a blunder. He had specified concrete at a particular strength without thinking of how the contractor was to place it. He had also been associated with a job designed by a very eminent engineer, and had been amazed to find he had used 1:1:1½ concrete with $\frac{3}{8}$ in. aggregate in one part of the structure, and mixes of similar unorthodoxy elsewhere. Consequently they had been able to place the whole of the concrete beautifully. Could Mr Walley make some observations on the design of the concrete mix for such structures?

Mr R. F. Stevens (Building Research Station) said that although civil engineers wanted to know actual stresses in concrete structures, at present it was only possible to obtain accurate measurements of strains. The Building Research Station had been concerned with measurements in large prestressed concrete beams in the Structures Testing Laboratory at Farnborough. The results were included in a paper⁷ at the Conference on Stresses in Service. Initial stresses in the concrete were calculated from observed strains in the structure and modulus of elasticity tests on concrete specimens. Subsequent stresses in the concrete were calculated from the losses of prestress due to the contraction of the concrete.

105. He thought that concrete stresses estimated in this manner would give a picture that was broadly correct, but it could not be highly accurate. In the case of the prestressed concrete beams at Farnborough, it was interesting to note that the difference in the extensions of the tendons between the two beams reported by the Author agreed well with the differences in observed concrete strains.

Mr E. C. Chaplin (Messrs Maunsell & Partners) remarked that §§ 44–57 spoke of principal tensile stress. Would Mr Walley say what he meant by reducing the stress to a safe value? What value had he in mind, and what were his reasons for choosing these values?

The Chairman (Professor S. R. Sparkes) said that he had been interested in the method of moving the water in tanks rather than the model in the tanks. He had seen this method used in Genoa some 15 years previously. Had Mr Walley any idea which system was to be preferred in tanks.

108. At the conference to which Mr Stevens had referred, data had been produced, particularly by Mr Elvery of University College, London, concerning the variations of between 3 and 6 in the moduli obtained in quite small concrete specimens, and also of measurements by the Centex method, where there were similar variations. If the modulus was used in association with strains to calculate stresses, some rather peculiar results, which he could not feel were correct, were obtained. Had the Author any views on the meaning of the stresses he had given? He himself believed that they were right in broad terms, but because of the variations in modulus it seemed that these results should be used with discretion.

109. The suitability of the designs of the concrete structures was probably better assessed in relation to the fact that the structures performed the function for which they were designed. The imprecise loading to which one was designing could put the structure in conditions for which it was not intended. At London Airport a couple of weeks before he had followed a fat man up the prestressed treads of the steps, and he remembered seeing the cracks opening and filling up with dirt! Any but an engineer might think this a rather unsuitable use of prestressed concrete in a minor context.

The following contribution was received in writing:

Mr J. K. L. Black (Senior Designing Engineer, New Zealand Ministry of Works) wrote that in Paper 6915 'Prestressed penstocks at Benmore'⁸ he and his co-Authors mentioned in their conclusions that elimination of the low-friction support bearings would be carefully considered in any future design of similar penstocks. The dust explosion gallery at Buxton was an instance of a simple medium friction foundation or support which might possibly be developed for prestressed penstocks, provided the losses in longitudinal prestressing forces through friction at the base could be determined with some degree of accuracy. This appeared to have been done at Buxton, but the details in the Paper were incomplete. Could Mr Walley indicate the total forces at the time of the stressing at the cable jacks and at the intermediate flat jacks, and give other available data which would be relevant in comparing the actual friction coefficient of the tunnel footing with the laboratory value?

111. Drying shrinkage for the 1200 ft gallery would be several inches if unrestrained and fully complete. Was the prestressing carried out after this was substantially complete? If not, was the measured 1.25 in. strain through prestressing considered to cover creep, temperature drop, and remaining drying shrinkage, leaving the concrete under some compression in the interest of waterproofing?

Mr Walley, in replying to Dr Bate, said that in fact if there had not been research undertaken, particularly into the fatigue and dynamic resistance of prestressed concrete, most of the structures described would never have been built. When the rocket engine test stand had been first conceived after the failure of the steel structure referred to in the Paper, some effort had to be expended in persuading engineers at the Ministry of Aviation that prestressed concrete was a viable solution. To this end they had been taken to the Building Research Station and been shown the work there, together with films taken during dynamic tests. It had not been easy to convince them but this was understandable in the light of the risks involved should a failure occur and he was glad to report that the stand had been very satisfactory. To answer the question as to whether the pay-off was satisfactory was more difficult since it was difficult to unravel costs in a £10 million contract. It was certainly a lot cheaper, but what was of much more importance was the speed at which it could be built as compared with the corresponding steel structures.

113. In answer to the question as to why the repeated loading was only 70% of the static loading in the R.A.E. laboratory, this was laid down for the test gear and steel bridges and was a criterion for the steelwork design. In relation to the prestressed concrete he was not at all concerned if the repeated loading was equal to the static loading.

114. Dr Bate had also referred to the extensions for the tendons at the R.A.E. laboratory. Here the results given in the Paper could be a little misleading. The theoretical extensions took into account assumed frictional losses, which had been less than anticipated, even taking into account triple curvature so that the forces had not exceeded those allowed. As to the future he thought that 85% might be a little too high; 80% would appear to be a more reasonable figure, but if the tendon profile were at all complicated or a very high price would have to be paid should anything go wrong with the stressing he would prefer to keep to the existing values.

115. In reply to Mr Harris, it had been stimulating to put new ideas into practice and to have clients who were willing to trust one's engineering judgement. It was very true that one had to be in on the ground floor to be able to influence decisions, but luckily this was nearly always possible in Ministry work. In answer to the specific question about explosive loadings, he said that it was perfectly true that a different material would affect the loading since the problem was a dynamic one. The equivalent static pressure was a function of the frequency of the structure and this in turn would be affected if the structure was cracked. In the case of the Buxton

tunnel it was, however, virtually impossible to calculate the frequency, as it was a cylinder lying on its side on the ground. Since perfect water-tightness was a criterion for other reasons mentioned in the Paper, cracking was not considered in relation to the design loads used.

116. Mr Harris had asked why the tunnel had not been circumferentially stressed. The Paper had attempted an answer—it was purely a question of cost. His own reluctance not to stress might be imagined, but the number of cables and the number of anchorages required to do it in any scheme were such as to eliminate it on grounds of cost. It had to be remembered that with all these jobs cost did come into it. Some people might have got the impression that if a Government research department wanted a structure or facility it only had to ask for one. In actual fact, there was a fairly limited cost, in the sense that only a certain amount of money was available for research. That sum had not to be exceeded, and it also took account of the whole of the mechanical equipment, which was not included in the costs given in the Paper. All the projects described had to be prepared within a cost budget.

117. He had had no experience of the use of high tensile bolts. It had not been an easy job persuading the R.A.E. to use a concrete hinge; one had to convince the client that he was getting a proper job, and it was not easy to put over such thoughts to people dealing with aircraft, and to get them to appreciate the properties of a material quite dissimilar to what they had been previously accustomed.

118. In answer to Mr Lowe, Mr Walley considered it very important that the final solution of any engineering problem should be simplicity itself, and he was very much against the idea of complicated solutions unless they were absolutely necessary. In all the cases described in the Paper, dynamic conditions and vibration were the governing factors in choosing the design solution and it was for this reason that prestressed concrete had been the chosen medium.

119. With reference to the question concerning the value of E , the Author's view was that the order of accuracy of the calculations achieved in this type of work did not warrant any closer determination of the value of E than that given in the Paper, and he was very well satisfied that a sensible value had been obtained in practice. Mr Lowe was quite right in stating that of course the measurements were those of strain and the stress had been calculated from them using an assumed value of E . The difference in strains was not between the ground floor and the basement slab but rather between the two directions in the basement slab.

120. Mr Walley thanked Mr Creasy for his contribution. He, too, had been much struck with the different approach to the subject which he had adopted since the previous paper 10 years before. This was probably caused by the newness of the subject at that time as compared with the ready acceptance of such solutions at the present time. With reference to his comment on the use of flat jacks, this could be considered as an insurance policy in that no-one had up to that time stressed such a long structure. The use of such jacks, as compared with the use of multiple stressing and multiple anchorage along the length, had, however, saved a sum of about £50 000.

121. With reference to the relative economies of prestressed concrete and other forms of construction he considered that it was important at the outset of the job to examine the requirements critically and to propose solutions using the best material for them. For example, in the case of the R.A.E. laboratory at Farnborough he had been pressed by the architect to use a concrete superstructure for the main test frame. He had refrained from doing this because of the increase in the weight which would have resulted. It was in the parts which were subjected to vibration or shock where prestressed concrete was considered to be the ideal material.

122. In answer to Dr Rowe the reference to the data he required was in the Paper. The original document had in fact been loaned to the Author by the Cement and Concrete Association, but no doubt Dr Rowe was also aware of the work done by the late Professor Magnel in Ghent on the effect of low temperature on prestressed

concrete. He was not yet able to give the data on the effect of explosions on the tunnel. This, however, was being collected by the Safety in Mines Research Establishment and would be made available at a later date. In general, however, the stresses recorded had not yet been as large as had been allowed for in the design. The only damage sustained by the tunnel up to the present had been to the steel arches and their connexions to the concrete tunnel. No damage had yet been recorded on the concrete structures. With regard to the stress of 14 000 lb/sq. in., he was very happy to say that Dr Rowe had convinced him many years before that this was a reasonable solution, but it was quite another matter convincing the client and other interested engineers. He appreciated that Dr Rowe might think him a little conservative, but felt that he had gone sufficiently far for the present.

123. The cube strength of the concrete in the hinge was 8000 lb/sq. in. He appreciated that it was a fairly low factor (less than 2 to 1). He could not answer the question on the thermal load directly. What he had had in mind was that the heat sink effect of such a large concrete structure would ensure that the rise in temperature and hence the thermal movement would be exceedingly small, whereas in a steel structure they could well be very high. In the case of the Building Research Station Laboratory one would expect very little movement because of the controlled environment provided.

124. Mr Walley thanked Mr Cameron for his additional remarks about the problems of constructing the tunnel in the exposed conditions at Buxton and was very conscious of the excellent work which the Contractor had put into the job. He considered that a great deal of the difficulty had come about because of the use of such a large amount of normal reinforcing steel in the transverse direction. The decision to use this method of reinforcing had been taken on cost grounds, but he was a little uncertain after seeing the job under construction as to whether the cost estimate obtained had been realistic: it could have been cheaper to have used prestressed concrete transversely as well as longitudinally. It should be stated that the Contractors when tendering had been made aware of the accuracy required and considerable trouble had been taken with the specification to ensure that it was possible to achieve it.

125. In answer to Mr Little, he realized that people would wonder whether he had been completely objective in arriving at the solutions adopted in the Paper, and that was partly why he had introduced the Paper in the way he had to draw attention to the vast amount of work which had been done using other materials. But he still felt that the solutions which had been adopted for these particular structures had been the best ones and had had no second thoughts after their completion. He had already answered the question of the stresses in the concrete hinges in reply to Dr Rowe. In answer to Mr Pearson he said that it must be appreciated that the designs for the Crowthorne floor and the Garston floor were carried out at different times and one would expect some differences in the second design. No problem had arisen at Garston because of water.

126. In answer to Mr Leyland, he had not considered using a bitumen layer. During the design stage solutions had been considered and the chosen solution was one which gave an adequate coefficient friction without increasing the costs enormously.

127. In answer to Mr Pullan, in general the design of the concrete mixes were left to the main contractor; only the strength at a given age had been specified. In the majority of the jobs described, however, with the possible exception of the Buxton tunnel, the placing of the concrete was very much simplified by the fact that prestressed concrete had been used as opposed to reinforced concrete.

128. In answer to Mr Chaplin, Mr Walley had always considered that the principal tensile stress should be looked at at two different limit states. Firstly, when the structure was carrying its normal design load and secondly when it would be carrying its ultimate design load. In general the principal tensile stress did not increase in

direct proportion to these two conditions and provided the structure did not fail because safe principal tensile stresses were exceeded, the principal tensile stress under design load could be reasonably high, say 200 or 300 lb/sq. in. One had always to be careful to examine what would be the result of a premature failure of one part of a structure.

129. In reply to the Chairman it had been thought for many years that the solution of moving water as opposed to the model would involve the use of a vertical tunnel to get rid of air entrainment and such a tunnel already existed at Feltham for testing among other things propellers. Such a design, however, for the larger quantity of water required for these tests had put such a solution out of court because of the costs involved. However, the horizontal solution which had been adopted for the structure described in this Paper had been proposed and model tests had indicated that this was a feasible solution, so that this piece of research equipment had been built within the capital costs allowed. He understood that the tank was working exceedingly satisfactorily. He was very glad to hear Professor Sparkes's remarks on the relationship of stresses, strains and moduli and he completely shared his views on this matter. Provided that they were right within the broad terms, the real criterion was whether the structure performed the function for which it was designed.

130. In answer to Mr Black the force in the cable jacks was 5×10^6 lb and at the intermediate jacking positions on completion of the stressing it was 2.45×10^5 lb before inflation of the jacks. The values given in § 19 had been calculated using the coefficient of friction given in the Paper. A considerable amount of the drying shrinkage would have taken place before the stressing of the gallery because of the time required for construction. The total strain recorded during stressing was essentially that caused by the prestressing, since the duration of the stressing operation was only 17 days and little drying shrinkage could take place in this time. The creep losses would be exceedingly small because of the relatively low stress in the concrete. It was certainly expected that the force in the prestressing cables would follow any further drying shrinkage since the extension at the cables was nearly 80 in. as compared to a few inches caused by the drying shrinkage.

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