

Collapse of Ynys-y-Gwas Bridge, West Glamorgan

R. J. Woodward and F. W. Williams*

Dr R. J. Woodward and Mr F. W. Williams

After publication of the paper, Dr C. Burgoyne (then of the Department of Civil Engineering at Imperial College) came across an article published in 1954 which described the construction of the bridge.¹² It confirmed many of the observations made during the investigation into the collapse. For example, the use of cardboard tubes around the longitudinal tendons where they passed between the segments and the insertion of asbestos packing between the beams were described. There was also information on the maximum concrete stresses, in particular it stated that the bridge had been designed for zero tension.

Mr P. J. Andrews, Northamptonshire County Council

I am concerned with the implication for bridge management of a collapse like Ynys-y-Gwas. There are a number of bridges in Northamptonshire which are externally stressed for various reasons. There is one with prestress in the joints of box beams. This is not unique. To put extra prestresses in old box beams, the beams can be spaced slightly and the cementitious film stressed in. In the light of this bridge collapse, this is dangerous. The loss of metal on a critical section must be looked at, rather than percentage loss across the total steel of the deck. 0.1% of the total metal is an erroneous statistic as it is not the critical problem.

66. The lowest point of temperature occurs at about 9 or 10 o'clock in the morning, because the bridge deck is slow to take up and give back heat. Consequently the minimum temperature is produced after the sun comes up because the bridge deck has not started to reabsorb the heat from its prestress temperature.

67. Would the Authors comment on the use of glue segmented work, as opposed to asbestos-filled structures?

68. In § 58 poor workmanship was mentioned. All bridges have an element of poor workmanship given that modern standards are much more careful about specifications than they were many years ago.

Dr L. S. Blake, Standing Committee on Structural Safety

It is important to investigate and report all collapses and failures of this type, whether they be of bridges or other structures. Preferably this should be without recourse to legislation, because when investigations of failures get tied up with legislation a lot of information useful to the profession gets lost or obscured.

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70. The Standing Committee on Structural Safety is very interested in this particular failure and, I hope, has been able both to give some help to the investigators and to encourage them to give their results the widest possible publicity. One of the lessons that has been learnt is that we are not good enough in this country at keeping records. It was very difficult to find out whether there were any other similar bridges that might be vulnerable. The Department of Transport and British Rail have adequate records of their bridges, but the same cannot be said for all other owners. With the reorganization of local authorities in 1974, some records were lost. Further information was lost more recently when the metropolitan counties were abolished.

71. In one respect, the investigation supports some findings of earlier work by the TRRL on the performance of tendons in post-tensioned concrete. Although there was severe corrosion elsewhere, the tendons were corroded very little, if at all, even in partially grouted ducts, if they were coated with a film of cement paste. In view of the probability of a number of partially grouted ducts existing in various types of structure, this finding is encouraging although, of course, the protection afforded by a thin film of paste can not be assumed to last indefinitely.

72. The Standing Committee had taken the view that the incidence of failure in a tendon in a post-tensioned bridge would be signalled by cracking, rust staining, and perhaps, in the worst case, deflexion. Apparently it was impossible to see any such warning signs at Ynys-y-Gwas Bridge. I believe that in the majority of cases some staining would be evident in the event of tendon corrosion, but a non-destructive method of identifying corrosion is urgently needed, not just for prestressed concrete but for reinforced concrete generally. Such a method seems to have defied all the efforts of the TRRL and organizations in Europe and in North America to produce. Is there any more comforting news from the Authors in this respect? What are the prospects of a good, non-destructive method of test?

73. Segmental construction has also been applied to buildings, and some may be at risk too. The publication of this Paper will do a great deal of good if it rings alarm bells so that people look at their structures more often and arrange periodic expert inspection.

74. There was a lot of experimentation with prestressed concrete during the period when Ynys-y-Gwas Bridge was built in 1953. Looking at the design and the construction of the bridge, and bearing in mind the knowledge and experience available at the time, those concerned might be complimented to some degree. The heavy corrosion that occurred at the longitudinal joints was not readily predictable in 1953, although it may be so now. After all, the sleeves of cardboard tube were a lot easier to obtain than steel ones and, in any case, those joints were going to close and stay closed once the bridge was prestressed and grouted. There was no thought of using salt on minor roads at that time, nor on many other roads. Where was the fault? It is only in recent years that more attention has been paid to waterproofing and draining bridge decks and joints. The trend that has created this particular problem is almost entirely the use of salt, so an alternative de-icer to salt would be very useful.

Mr P. H. Dawe, *Bridges Engineering Division, Department of Transport*

At the end of the Paper one still wonders why a bridge could carry loads one day and suddenly collapse overnight, under no loading at all.

76. Regarding § 61 I agree that it would be wrong to draw too many conclusions about the state of modern bridges from this one failure which is an early

example of an unusual design. However, all bridge owners must be worried and the alarm bells have begun to ring. At the Department of Transport a mini-study is being initiated of nine typical segmental post-tensioned bridges to assess their condition, and in particular the state of the tendons to see if there are any signs of corrosion. As well as looking at the condition of the bridge, the study aims to develop guidance for inspection, so that ways can be developed in which bridges of this type should be examined and critical points identified for examination. If the study does show there is cause for alarm, then guidelines to form the basis of a wider inspection programme will be available.

77. Paragraph 59 deals with the state of precast units. At Ynys-y-Gwas, workmanship and particularly the materials in the precast units themselves were of a pretty high standard, and yet all this effort was let down by poor detailing of the joints. It is a reminder that a lot of time can be spent on global design but in the end the detailing—the attention to the small points—is vitally important for obtaining long-lasting durable structures.

78. The Authors have not looked very much at the future and whether or not steel tendons should continue to be used—especially when there seems to be more salt on our roads than on our tables. Do the Authors have any ideas about alternative material? The Germans have constructed a footbridge and a highway bridge using material called polystahl which is glass fibre in polyester resin. The black plastic coating protects the glass fibre tendon from surface drainage. Could the Authors comment on the use of alternative materials to steel for prestressing tendons?

79. The use of grillage analysis in the structural assessment of the bridge is referred to in § 33. The Department of Transport has started assessing its older short-span structures, and analysis is an important part of assessing the strength of a structure. Even with the plethora of analysis programmes available, it is not always clear what are the correct values of stiffness parameters to use. In the Authors' investigation how were the parameters chosen and was any attempt made to verify the parameters used from tests on the salvaged sections?

Dr K. A. Gallagher, *Transport and Road Research Laboratory*

Previous work carried out by the TRRL⁶ has shown that both fully grouted and partially grouted ducts can offer good protection to prestressing tendons, so long as chlorides are excluded. There is often a fine coat of cement paste on the steel in partially grouted ducts. Provided the environment within the duct is dry and free from chlorides, there is little or no likelihood of corrosion.

81. The problem is how to inspect the condition of the tendons, particularly where they are fully grouted, in the places where chloride contamination is most likely, such as at the joints in segmental construction. At present there is no reliable non-destructive testing method for examining the wires, and the study of their condition being carried out for the Department of Transport will rely on careful drilling and visual inspection, together with sampling for chlorides.

82. It is important that all structural collapses are investigated thoroughly. Examination needs to start as quickly as possible, before the evidence is cleared away, because it is easy for vital pieces of information to be removed or destroyed.

Mr W. A. J. Sketch, *Buckinghamshire County Council*

I was formerly an assistant county engineer with West Glamorgan County Council, and before that I was a bridge engineer with Glamorgan County Council.

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At an early stage I came under the influence of Professor Sir Alfred Pugley's dictum: if you see something peculiar and something fails, look for clues in people, not in what is materially wrong. From the early 1950s to the mid 1970s nearly 300 new bridges were built in Glamorgan. Most of those bridges were able to be checked for abnormal loads, and were checked. Ynys-y-Gwas Bridge was built by a relatively small borough, but who designed it?

84. A possibility was that because the Glamorgan bridge engineer who would have overseen the design and construction was terminally ill, maybe checking was skimped; although, by the time his successor was appointed, bridge calculations in the county were well organized and were easily able to be checked.

85. In the late 1950s and early 1960s staff in Glamorgan were designing for no tension in bridges, simply because it was known the chief bridge engineer at the Ministry of Transport would not approve calculations which had allowed tension. But numerous other bridges were being designed to the building code which did allow 150 lb/in² tension. If Ynys-y-Gwas Bridge was designed for tension it is likely it was designed by a structural engineer rather than a bridge engineer.

86. Do the Authors know anything more about the design and how it arose? It is an unusual type of bridge for Glamorgan. Why was this particular type of bridge chosen, and how did it come to be there when surrounding bridges constructed at that time were so different?

Mr A. N. Hendley, Consulting Engineer

I have been involved in a number of collapses and different types of structures and there seems to be a randomness in them. The worst mistakes by designers do not necessarily have the worst consequences, whereas a trivial mistake can have serious consequences. Therefore, trying to find out who specifically designed a bridge does not help.

88. One of the things engineering lacks is a virus. Doctors can locate a virus which they can neither see nor describe but which nonetheless they know can kill. This happens with structures as well. Structures which fall down can be investigated with terrific care, but in the end it is more difficult to prove why they were standing one day than why they fell down the following day.

Mr K. Sriskandan, Mott, Hay & Anderson, now Mott, McDonald

There is one point in the investigation that is still not clear. The Authors say that the joints could have opened under load and yet there was no evidence of fatigue. It is well known that if there is a wide crack in a prestressed concrete beam, the stresses in the cables will be so high as to cause failure by fatigue. So, were these wires examined under an electron microscope for evidence of fatigue? If there was no evidence of fatigue, there could not have been tension causing the joints to open, suggesting that there was something wrong with the calculations. In reply to *Mr Sketch's* earlier question, I can say that the design rules of the time were taken from *The First Report on Prestressed Concrete* published by the Institution of Structural Engineers in 1951 and they did not permit tension in prestressed concrete bridges.

90. I do not consider that the implications for modern day segmental construction are as serious as suggested by the Authors. The joints of Ynys-y-Gwas Bridge were 25 mm wide with mortar pack, whereas in subsequent segmental construction, joints were of fine concrete 75–100 mm wide. In these later designs, the concrete would have been well compacted and therefore would not have been

as permeable as the earlier mortar. Furthermore, it was suggested that there could have been some chlorides in the sand used for the mortar joints of Ynys-y-Gwas but calcium chloride in any form has been prohibited for quite some time. When it comes to glued segmental construction, the epoxy resin which is placed in the joint between match cast segments results in a relatively impermeable joint.

91. The Authors said that provision should be made in new designs to inspect the tendons. This can be done where cables are external to the section such as box girders, and has been done in many bridges, especially overseas. In Long Key Bridge in Florida, USA, the external tendons were grouted in a polyethylene duct, but were inside the box section which was made up from match cast segments with no epoxy or any other material in the joints. However, in smaller bridges the sections will not be large enough to facilitate inspection, and therefore cables have to be grouted for protection. In the past, Freyssinet tendons had formers effectively separating each wire with sufficient room for the grout to get through. However, even that type of tendon could twist within the duct. The Magnel-Blaton tendon had grills in rectangular holes which could not twist and could therefore be grouted totally.

92. So there are two solutions, both of which are extremes: either go back to something similar to what was done in the past and make sure that the tendons are grouted properly, or have external tendons of some non-corrosive material or steel protected in one way or another. Lastly, improved inspection and testing techniques should not be left for the longer term, but should be developed very soon for existing structures.

Dr F. Walley, Consultant

This seems to be becoming a vexed question of the allowable tensile stress for concrete in bridges. On the committee on CP 115 of the prestressed concrete code in the 1950s the representative for the Ministry of Transport said quite emphatically, 'You can do what you like in the way of tension in prestressed concrete but the Ministry will not accept any tension.' I believe that was the official standpoint at the time.

Dr C. J. Burgoyne, Emmanuel College, Cambridge, formerly Imperial College, London

The Paper implies that if a single wire in the tendon fails, the prestressing load will be shed into adjacent tendons. However, I believe that when a prestressing tendon which is in place and is grouted corrodes, the prestressing force is lost locally. There is no tendency to shed the load to adjacent tendons. If additional loads are applied to the structure, then these loads will be shared in proportion by the remaining tendons: prestress is not shed in this way. This makes the job of explaining why the bridge stood up one day and fell down the next more difficult because there is no additional load being put on the prestressing tendons.

95. Should such structures be approved in their subsequent lifetime by load testing? Load testing of structures is not well liked, but as there was no possibility of detecting in advance that Ynys-y-Gwas Bridge was in danger of failing, is load testing not the only reliable means of ensuring structural adequacy?

96. Points have been made about the design of the structure. A paper¹³ which I read, stated quite clearly that the structure was designed for no tension. This indicates that non-corroding tendons, such as those under test at Imperial College,

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are a more sensible alternative. The initial cost of non-corroding tendons is higher than for steel tendons, but the cost of subsequent remedial works overcomes this initial cost penalty.

Mr D. J. Lee, G. Maunsell & Partners

Mention has been made of the need for a legal requirement for early notification of failures, such as required for aircraft and railway accidents. Just because bridge failures and building failures are rare, does not mean that notification should be left to the professional responsibility or good relations between the engineers and authorities. I think there should be a procedure that ensures that as of right experts are invited very early on to a site after an incident while evidence is fresh.

98. A cadre of specialist inspectors is obviously outside the resources of many county councils and local authorities; but there should be such a cadre of people available to give assistance, because a maintenance engineer or a normal trained civil engineer cannot be equally expert on all danger signs in a multiplicity of structures and materials.

99. As-built drawings cannot always be relied upon, and so common sense must be used. It is important to conduct some kind of desk study or examination of the possible bridge problems that can occur in any part of the country. Some bridge types are more sensitive than others, and it is important to try to identify these.

100. As the TRRL has been brought in on the bridge side, so the Building Research Establishment should be involved with building problems, when they occur. Occasionally the Department of Transport says that it is only directly responsible for the Department's own bridges. All roads, trunk or otherwise, are used by the public, and so regardless of ownership there should be collective concern about the correct identification of possible danger areas.

101. The design of the Ynys-y-Gwas Bridge exhibits the curious case of a sudden collapse rather than a progressive collapse. This is a philosophical aspect of design. This bridge with its transverse prestressing did not show the problems that were developing.

102. Can I take issue with the question of full prestress? This is a dangerous remark to make in 1988 when design has progressed considerably since 1953. Full prestressing (or zero tensile bending stress) is a misnomer because this is only present under a specific loading. Temperature conditions, or thrusting conditions from abutments or bearing slippage, for example, contribute to the stress condition of the bridge. The bursting tensile stresses in anchorages cannot be ignored. The prestress changes all the way along the bridge, and in many cases the stress is not as was designed. It is misleading to talk about no-tension conditions because it is possible to design structures with partial prestress which balance safety against potential brittleness or overstressing. The essential matter is the amount of reinforcement provided, not whether all or only some of it is prestressed. The edge beams of this bridge were supporting the interior beams by way of the transverse stressing. The exterior beams might thus be considered to be too stiff. If that had not been so there may have been deflexion visible and hence provide the warning of collapse which is normally assumed with flexible prestressed structures.

Mr T. A. Nicholson, Member

Into what depth did the Authors carry out the investigation for fatigued wires in the structure? Was any half-cell potential or resistivity testing carried out prior to the collapse, and would anything have been gained by doing so?

Mr M. N. T. Cottell, *County Surveyor, Kent County Council*

Was any research done on this minor road to see how often the road took a vehicle with an HA loading? Certainly a 38 t truck is usually not an HA loading, so is the incidence of tension quite rare at this particular location? If it is rare, what does that point to? Does it point to the tendons in the bottom flange being subjected to greater water corrosion through cracking because the beam came into tension? If so, were those tendons more or less corroded than those in the top flanges? I suspect that on a road of this character the incidence of tension due to HA loading would be very rare indeed. Or perhaps the answer is that there is tension when a 38 t lorry passes over the structure.

Professor C. J. F. P. Jones, *Newcastle University*

The failure of this bridge was essentially caused by de-icing salts. The Authors state in their Paper that there was very little evidence of corrosion products in their investigations. This is not unusual. Quite often no staining is seen although there can be extensive corrosion. This is particularly apparent with some bridge abutments.

106. The main problem at Ynys-y-Gwas was that the de-icing salts got into the structure at the point where the concrete or the packing was very poor: the cover was not sufficient, and the compaction and the curing in the area where the beams join together were faulty. Pre-tensioned or precast concrete manufactured to factory standards does not seem to have been a problem. This bears out studies elsewhere.

107. Problems occur in those areas where de-icing salts are able to penetrate to the prestressing cables or strands, either because the cover is deficient or because the concrete is deficient. An example of this is a well known post-tensioned box structure on the A1 in Yorkshire, with external cables. Being external cables they have been given an element of protection by being encased in concrete placed in situ within the boxes. The structure has a curved vertical alignment, and at various points along the deck salt water can drain into the concrete boxes directly onto the in situ protective concrete surrounding the post-tensioned tensioning cables. There is very little rust staining, although there is plenty of evidence of long term drips of salt water. The concrete surrounding the post-tensioning cables was dug into and it was found that some of the cables had corroded. This is a case where protection to the external cables was a problem, and my argument is that one should not necessarily look first at cables inside precast, factory made products, but rather at cables passing through in situ joints and concrete which is exposed to de-icing salts.

Mr C. Hannah, *Consulting Engineer*

Although corrosion of the steel weakened the structure at Ynys-y-Gwas, the cause of the collapse hinges on what was different between the day of collapse and the day before. In the Paper there is no mention, other than the date of collapse, as to what was different between those two days. The first week in December was bitterly cold. Was it a particularly cold night which made the difference? The chances are that the bridge was put up in the summer and as it was a simple span bridge on building paper bearings, there is automatically built-in tension from the friction of the bearing force. There may be tension anyway, as beams tend to contract in the colder weather, so that there is going to be tension built in and a

chance—just at a critical time when the salts are going on the road—of a bearings problem which could contribute to the final collapse of this beam. What did the Authors do to investigate the peripheral factors on this beam, both of temperature and of bearing conditions?

Mr A. C. E. Sandburgh, Messrs Sandberg

I should like to comment on the general question of the examination of failed bridges.

110. The procedure adopted for an aircraft accident enables the specialist investigator to be on site as early as possible to collect evidence which can disappear with time. Much valuable detailed surface evidence may otherwise be lost, and an early examination of the corrosion may assist in identifying the type and method of development. Exposure to water and atmosphere together with damage resulting from the salvage work can destroy evidence. Photographs taken by local engineering staff—while obviously valuable—will not necessarily provide the records which the specialist investigator requires.

111. In this instance Dr Woodward, the leader of this investigation, did not see the bridge until six days after the collapse and his visit was only as a result of a call from a technical journal. In due course the TRRL became positively involved. Portions were sent to the TRRL for testing and investigation as described in the Paper, which was published some 2½ years after the collapse. This raises the secondary issue that this is a long time for the information to be generally available. It has been suggested in the Seventh Report of the Standing Committee on Structural Safety that a warning system be set up to alert the TRRL of bridge collapses, so that a specialist investigator can be on site immediately as a matter of right.

Mr P. A. Jackson, Gifford and Partners

There has been much discussion of the lack of warning prior to failure; in particular of the lack of any visible cracking. Ironically this may, in part, be the result of the good distribution properties of the deck. Some time before this failure occurred, colleagues from Gifford's undertook a study of the effect of tendon corrosion on the behaviour of bridge decks. They predicted that in beam and slab type decks, with their relatively poor distribution properties, there should be extensive cracking in the worst affected beams before failure. However, a bridge such as Ynys-y-Gwas has much better distribution properties which are more comparable with those of box type structures. For these, my colleagues predicted that—although a greater total loss of tendon area would be required to cause a failure—there would be very little warning. The failure of Ynys-y-Gwas has confirmed this prediction.

113. There has also been much discussion of the difficulty of detecting or measuring the corrosion in the tendons. An alternative approach, which has not been mentioned but which can be very useful, is to assess the stress state in the concrete and to use this to deduce the state of the tendons. In the case of a segmental structure such as this, the stress state can be determined by fitting strain gauges across the joints and observing the change of reading with either time or loading. Alternatively the residual stress measurement approach can be used. Colleagues from Gifford's have developed the techniques for doing this and have successfully applied them to bridges in service.

114. An aspect of the collapse the importance of which, I believe, has been

much exaggerated is the apparent absence of any vehicles on the bridge when it collapsed. In my former role, at the C&CA, I tested a number of fairly large concrete structures to failure. None of them collapsed within ten seconds of the full load being applied while, in some cases, there was a delay of several minutes. It would only take a vehicle some three seconds to cross Ynys-y-Gwas Bridge. Thus, even if this collapse was caused by a vehicle, the vehicle would have been well away from the structure before it failed. It may be possible to tell from the number of tendons which appear to have failed in advance of the collapse whether, immediately before the collapse, there were enough intact tendons to support a significant live load. Has any attempt been made to do this?

115. Finally I would like to endorse what *Mr Lee* has said about the irrelevance of the discussion of the no-tension rule. Whether or not a structure complies with this rule in design is dependent on the loads and effects which are considered in the calculations; for example, whether one considers differential temperature, shrinkage etc. and what live load one takes to be the service live load. Thus the implication that—whether the structure is designed for no tension or for 150 lb/in² tension—just 1 N/mm² is of fundamental importance is incorrect, because the calculated stress could vary by a much greater margin. The Paper appears to suggest that the original designer and the most severe assessment to BS 5400 differ on the service stress by as much as 10 N/mm².

Mr D. B. Dawson, British Rail, Western Region

In § 15, reference is made to cracks in both the I beams and the edge beams, and the comment is made: 'Their cause has not been identified.' In view of the fact that further investigations have been carried out and some of the other mysteries have been solved, has anything further been found out about these cracks?

117. It is stated in § 55 'An assessment requires an estimate of the remaining sectional area of the steel yet there are no non-destructive methods for doing this on structures such as Ynys-y-Gwas.' Was the use of radar for investigation of the steel considered? British Rail have been using radar with good results to investigate the location and dimensions of steel bars, bolts and other items in various building materials, such as concrete; stone-work and timber.

Mr P. D. Baker, White Young Consulting Engineers

In 1974 a post-tensioned, precast concrete roof beam 18.6 m long collapsed due to corrosion of the tendons. The typical section of the beam is shown in Fig. 24 and the elevation in Fig. 25. The beam had been constructed of three precast concrete units assembled in line and stressed together with dry packed mortar joints.

119. At the time of collapse the beam was 14 years old. It was visually exposed in the roof of a warehouse and no signs of distress had been noticed. Failure occurred at one of the joints. Examination showed that the tendons were severely corroded in a manner very similar to that illustrated in Fig. 11. The exterior of the beam showed no indication of the condition of the tendons.

120. A programme of testing was undertaken which included the determination of chloride content in the concrete at various points along the beam. The values obtained are shown in Fig. 25. The values in the bottom of the beam unit immediately to the right of the point of failure are high compared with those immediately to the left of the point of failure and with other locations in the beam.

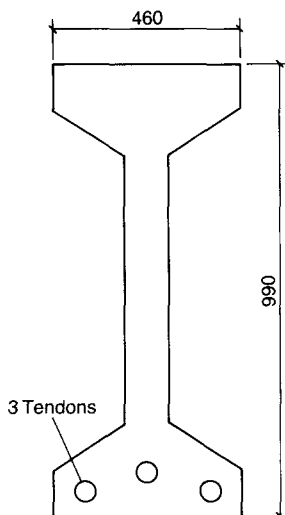


Fig. 24. Cross-section of a beam of a post-tensioned precast concrete roof which collapsed due to corrosion of the tendons

Examination of the tendons and ducts shows that the tendons and ducts immediately to the left of the joint had virtually no corrosion and that the severe corrosion of the tendons and ducts occurred immediately to the right of the joint. It might be concluded that the significant change in chloride content across the joint had been a factor in causing the severe corrosion at the joint.

Mr J. R. Saunders, Travers Morgan

Travers Morgan assisted the TRRL in their investigations by carrying out simple structural assessments. Although the Authors have prepared and presented an excellent Paper, I feel that some of the topics raised during the meeting could be answered in more detail.

122. A further paper is planned which will describe the current research being undertaken into the use of mathematical models to predict failure behaviour of post-tensioned structures. This work will be calibrated against the load tests carried out on the edge beams recovered from the bridge.

123. One contributor commented that as wires broke, prestress would be lost and not redistributed. While this is true for prestressing forces, it is not true for externally applied loads. As corrosion takes place the area of steel is reduced; the strain relating to the initial prestress remains constant, but increases to the point of breaking under the action of external loads. The load redistribution described in § 49 refers to the effects of externally applied loading, including self weight, which occur prior to collapse. The actual collapse mechanism is complex and depends upon the relative corrosion of adjacent wires or tendons, the length over which corrosion and loss of bond occur, the location of tendons within the structure, the transverse stiffness and the distribution of externally applied loading. The simple calculation referred to in § 50 regarding the effect of temperature movement and

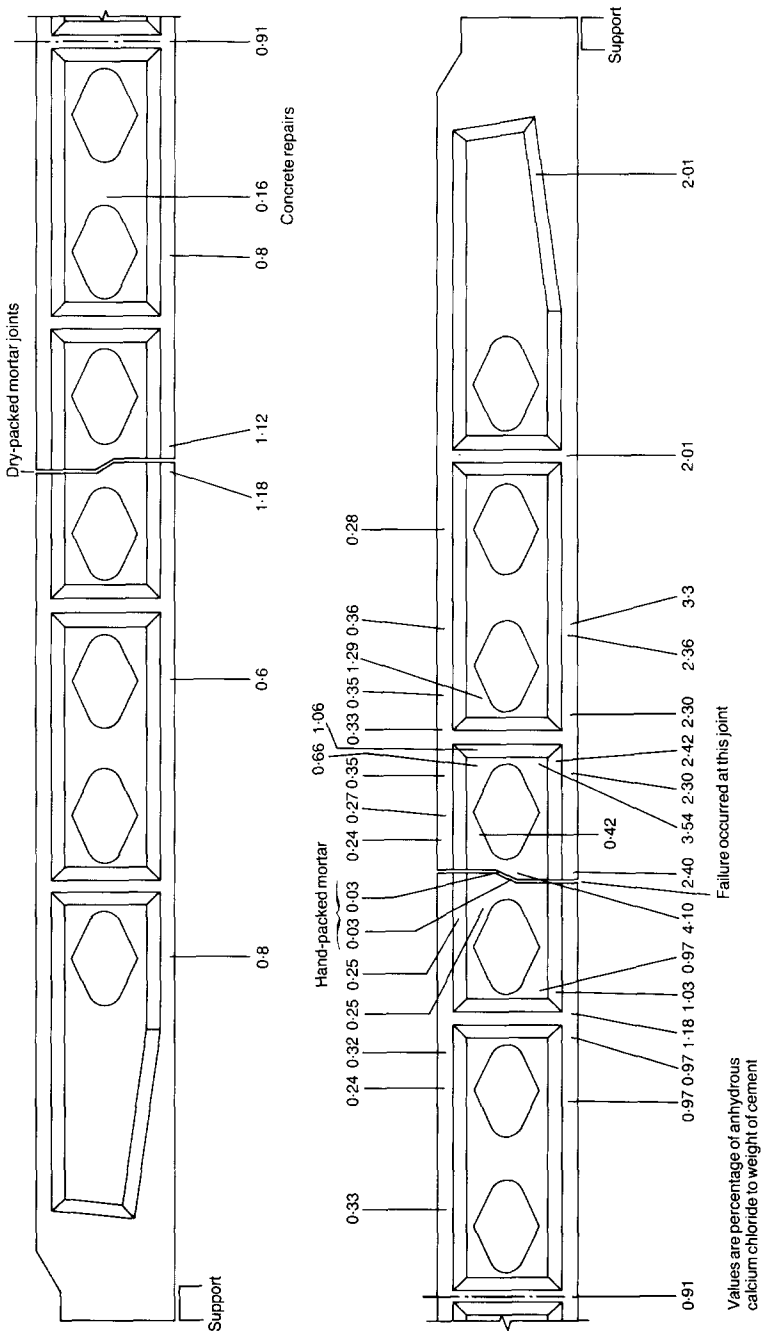


Fig. 25. Elevation of roof giving percentage of anhydrous calcium chloride to weight of cement

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bearing friction was based on an assumed coefficient of friction equal to 1.0. This was considered to be a reasonable upper bound value for smooth concrete surfaces to the bearing shelf and precast beams, with an allowance for adhesion arising from the bituminous building paper.

124. Although the 1954 paper by H. Kaylor¹² gave the original design parameters for the bridge, the as-built condition may not have reflected the designer's assumption in respect to long term prestress losses, creep, etc. Simple analyses were therefore carried out on possible parameter spectra and from these it was hypothesized that tension cracks may have occurred. Although tension cracks may have increased the corrosion rate, I believe the emphasis placed on design for no tension made by several speakers is not of prime importance in this case as the principal problem was believed to be chloride attack emanating from de-icing salts percolating from above and not from the soffit.

125. I consider that the investigation's main findings as given in § 58, were: (a) design and construction details led to localized corrosion of the tendons; (b) the collapse of the bridge was sudden, without prior warning, i.e. it did not exhibit the ductile type of failure expected from prestressed concrete structures. I believe both aspects are important and that many prestressed concrete bridges with bonded tendons could fail suddenly, without prior warning, if significant localized corrosion of the prestressing tendon occurs. This is especially true if the secondary longitudinal reinforcement is very light or non-existent.

126. It therefore follows that the concern of the Standing Committee on Structural Safety referred to in § 53 is justified and that further research into the assessment of existing structures, both physically and mathematically, needs to be given priority.

Dr Woodward and Mr Williams

Mr Andrews expressed concern about the implications for bridge management. No one would argue the need for improved practices. Lack of resources and the general trend to concentrate on purely remedial measures are underlying reasons for bridge maintenance having been the poor cousin to the design and construction of new bridges. However, many concrete and steel bridges built in the 1950s and the 1960s are now displaying problems in service, accentuated by the ever increasing use of de-icing salt. Bridge maintenance, assessment and the resulting work on repairs, strengthening or replacement are now major industries in their own right.

128. One lesson relating to bridge maintenance procedures, highlighted by the Ynys-y-Gwas collapse, is the need for a bridge construction file to be compiled giving detailed facts and data which can be used subsequently in the bridge's management. This file would supplement as-built drawings which are now systematically retained, although their accuracy and comprehensiveness could be improved particularly in regard to alternative designs and proprietary systems. The Authors agree with *Dr Blake's* comment about the inadequacy of the records which have been kept in the past and the frequency with which they have been lost.

129. The small loss of section is critical (§ 65). Corrosion did not occur uniformly over the structure but was localized to the joints between the units, and the volume of metal lost was very low. Therefore there was very little rust staining and what did occur was hidden from view.

130. *Mr Andrews* asked about the use of glued segmental structures and *Mr Sriskandan* commented that the epoxy resin that is placed in the joints between

match cast segments gives a relatively impermeable joint. The Authors would not accept Mr Sriskandan's views. Segmental bridges have in-built lines of weakness at the joints no matter how joints are formed and sealed. Where joints are glued it is not known how the glue will perform over a long period, both in terms of physical properties and resistance to the various chemicals which are transported by road in bulk. It is easy to look back with hindsight—all the Authors are trying to do is to look forward and offer words of caution.

131. Several contributors referred to the effect of temperature. The Authors agree with *Mr Andrews* that the lowest effective bridge temperature occurs during the morning (probably a little earlier than the 9 to 10 o'clock he suggested) so Ynys-y-Gwas Bridge would have been cooling down at the time of collapse and this may have been a contributory factor. *Mr Hannah* commented that the first week in December 1985 was bitterly cold. The Authors' records show that early December was comparatively mild following a colder spell in late November. Investigations of the effect of temperature and bearing condition are referred to in § 50.

132. *Dr Blake* suggested that it is important to investigate and report all collapses and failures of this kind. This received considerable support from other contributors and the Authors would also agree.

133. At present there are no non-destructive methods for detecting corrosion and fracture of post-tensioned tendons. *Mr Dawson* asked about the application of impulse radar. The majority of tendons in post-tensioned concrete are encased in a metal sheath which would reflect all the energy thus giving no information about the condition of the tendons or grouting. Some trials have been undertaken on unlined ducts but with little success.

134. It would be unfair to criticize the bridge designer for the deterioration that occurred. The Authors agree with *Dr Blake* that it is the increased use of de-icing salt that caused the problem not poor design, and this could not have been anticipated by the designer.

135. The Authors would not disagree with any of the comments made relating to the mechanism of collapse. To sum up all the views expressed, it is highly probable that a comparatively heavy vehicle crossed the bridge a short while before collapse, triggering yielding of critical cables. The load was redistributed to adjoining cables and beams which were incapable of carrying their increased share of the load, albeit only the self weight of the bridge. The overall situation was exacerbated by the prevailing low temperature which may have induced further tensile stresses in the deck due to the restraint caused by the rudimentary bearings.

136. The development of polystahl and its use in a small number of bridges in Germany is of great interest. Although such developments are welcome, the Authors caution against excessive use of new materials. New materials should be carefully monitored so that information on their long-term performance can be gathered as quickly as possible.

137. With regard to the values of parameters used for the analysis, and the transfer of load between wires as fractures occur, the Authors have nothing to add to *Mr Saunders'* comments.

138. *Mr Sketch* asked a number of questions about the history of the bridge. The original design was by engineer(s) working for the former Port Talbot Borough Council and as commented by *Mr Sketch* it would have been customary for the designs to be checked by bridge engineers working for the County Council. However, in the case of Ynys-y-Gwas Bridge, a major concrete precastor from East

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Anglia offered an alternative solution utilizing a consultant's fairly new proprietary post-tensioned beam design. This was accepted. The Council workforce placed the precast units on falsework, formed the joints and post-tensioned the beams.

139. Prestressed bridges of similar spans, built only one or two years later in West Glamorgan, utilized precast beams with construction joints and not mortared joints. These beams had been cast adjacent to the bridge site and then lifted into place. It has been found that the workmanship at the construction joints was very good and to date no serious corrosion has been found.

140. Two or three years after Ynys-y-Gwas Bridge was built, similar bridges were designed with an in situ reinforced slab over the beams. This gives much better protection to the prestressing cables.

141. *Mr Sriskandan* asked whether there was any evidence of fatigue. A number of wires were examined under an electron microscope but no evidence was found. This does not prove that there was no tension under HA loading since the loads required to open the joints may have occurred relatively infrequently. The initial calculations showed that there is tension when a 32 t lorry passes over the structure. However, subsequent analysis has shown that the transverse distribution of load may be better than was first assumed thus reducing the tension under load.

142. The Authors do not agree that the presence of formers around the tendons necessarily leads to better grouting since the formers interrupt the flow of grout. It was evident that even where ducts were fully grouted severe corrosion occurred (Fig. 13). Full grouting does not guarantee protection against corrosion.

143. Several contributors commented on the question of allowable tensile stresses in the concrete. In terms of the corrosion of the prestressing cables, the Authors' view is that this is of little relevance since chloride penetration occurred through the highly permeable joints.

144. The Authors are not enthusiastic about load testing and believe it should only be used as a last resort. Consideration would have to be given to effects which would not be presented properly in any static load test—for example dynamic loads, temperature and braking. It would also be necessary to predict deformations to guard against failure of the structure.

145. As described in the Paper, the bridge was subjected to what could be called the design load (i.e. full HA loading) in nine traverses of an abnormal load in 1981—a matter of only four years before collapse of the bridge. Clearly the rate of deterioration of the prestressing cables had been rapid since 1981.

146. This highlights one of the problems of load testing. Loading a bridge to its full design load confirms that it can carry that load on the day of the test but gives no indication how much longer it can go on carrying that load. Overloading a structure to check that it has reserves of strength may open cracks or cause deterioration that would not otherwise have occurred. If loading does cause failure, it may present a difficult exercise to explain to the elected members of the County Council and the public at large the fact that the County Engineer had, in the course of the test, destroyed what appeared to have been a perfectly satisfactory bridge.

147. There were numerous comments on the absence of warning signs. The Authors believe there were two reasons for this. Firstly, corrosion products were not visible for the reasons given in §45. Secondly, the load distribution properties of the bridge were very good, and the Authors agree with the comments made by

Messrs Lee and Jackson. The absence of visual deterioration is one of the main lessons learned from the collapse. Bridge maintenance engineers have to be more aware of possible hidden defects in bridges and not rely totally on superficial visual inspections.

148. West Glamorgan County Council engineers had not carried out any half-cell potential or resistivity tests on the bridge before collapse. Such measurements had been regarded as being of dubious value on post-tensioned concrete. However, in the absence of any alternative tests, the technique is being used on the bridges in the Department of Transport survey referred to by *Mr Dawe*.

149. In answer to *Mr Cottell's* question, there was no evidence that the condition of the tendons in the bottom flange was any better or worse than elsewhere.

150. In § 106, *Professor Jones* seems to have misunderstood the point at issue. The quality of the concrete was first class, the cover to the reinforcement was adequate, and the reference to compaction and curing is irrelevant. The chlorides had penetrated the highly permeable high alumina cement mortar packing in the transverse joints, and the longitudinal joints were virtually open save for the asbestos packing which itself acted like a sponge.

151. The Authors fully agree with *Professor Jones* that inspections of prestressed structures should be concentrated at points or lines of weakness in the structure, for example mortar joints, construction joints, anchorages adjacent to leaking joints and any cracked sections.

152. The Authors agree with suggestions put forward by *Mr Jackson* for monitoring but this must be done carefully. Mounting gauges across the joints requires continuous monitoring. Electrical resistance strain gauges are liable to drift over long periods of time and vibrating wire can not easily be monitored continuously. This returns to periodic load testing which is discussed above.

153. The measurement of residual stress in the concrete provides useful information but it is only relevant to that part of the bridge adjacent to the core. No attempt was made to determine the remaining sectional area of the tendons before collapse. To do this with any degree of accuracy would have been prohibitively expensive. While it would have given an indication of the live load that could have been supported it is unlikely that it would have helped explain the collapse mechanism.

154. No further measurements have been carried out to determine the cause of the cracks in the edge beams. They were probably due to plastic settlement of the concrete around the ducts.

References

12. KAYLOR H. A recently built roadbridge in prestressed concrete. *Civ. Engng Publ. Wks Rev.*, 1954, 49, No. 580, Oct., 1061-1063.