CRACKING IN PRESTRESSED CONCRETE BEAMS DUE TO ASR IN CABLE GROUT

C Rajkumar and A K Mullick
National Council for Cement and Bldg. Materials
New Delhi, India

The manifestation of cracking observed in prestressed concrete beams has been explained as due to ASR phenomenon occurring within the cable ducts. Using finite element modelling technique, it has been shown that the macro-cracking in concrete will initiate inside the beam and progress to the outer surface. The cracking not only increases the risk of corrosion to prestressing steel but also alters stress levels and deformation characteristics.

INTRODUCTION

During the late 1960s, while laying a new section of railway line, a number of bridges spanned by prestressed concrete (PSC) beams were constructed. Each of the 18 metre long spans, which supports the deck for the railway line consists of two I section beams with transverse diaphragms joining them together. The beams were precast and prestressed using post-tensioning system. After placing the beams in their final position, the deck slab was cast to form the configuration shown in Fig.1. Within a few years after construction, appearance of hair-line cracks on the concrete surface was reported. As the cracking developed further and became evident on almost all the beams, the beams became the subject of investigation dating back to 1977.

In 1990, the authors' organisation was commissioned to carry out a thorough investigation into the causes and the likely consequences of the cracking. Extensive field investigations, petrographic examinations and chemical analyses on concrete samples and strength tests on extracted cores were carried out to assess the quality of concrete in the beams and it was concluded that the concrete had neither deteriorated nor did it display any of the diagnostic features associated with alkali silica reaction (ASR). Further studies demonstrated that the expansion of the grout placed inside the prestressing cable ducts was the most probable cause of cracking and ASR in the grout mix could have caused the expansion. In the following, a description is given of the approach adopted to identify the problem of grout expansion. The study included theoretical analysis based on finite element technique to simulate crack initiation in the beams.

MANIFESTATION OF DISTRESS

Two distinct features (Fig.2) relating to the distresses were observed: (i) Longitudinal cracks on all three faces of the bottom flange generally following the cable profile; and (ii) cracks of a criss-cross pattern in the end block region, in addition to those following the cable profile. The cracks were classified as dormant i.e., not opening and closing as a result of loads, temperature effect, etc. However, from the documentation kept on the distress features, the width and length of cracks were noted to progress with time.

It is reported by Libby (1) that cracks following the path of post-tensioning cables are likely to occur due to the following causes: (i) Settlement of plastic concrete below the cable ducts (ii) Excessive grouting pressure within the cable ducts during grouting operations, and (iii) Increase in the volume of grout after it had hardened.

Plastic settlement of concrete or "shadowing effect" at the underside of cables is generally expected in deep webs and not in shallow sections such as the case under investigation. Moreover, the fractured surface of cracked concrete was observed to traverse through aggregates, pointing to the fact that the cracking had occurred after the mortar phase had matured and gained sufficient strength. This information conclusively delinked plastic settlement from the distress noticed.

Cracking of concrete during grouting operation could be expected in cases where the cable ducts of large size or square cross section were used or the concrete cover provided was smaller compared to the diameter of the cable duct. In the present case, the cable ducts as shown in the construction drawings were of normal size and circular in cross-section and the cover measurements taken on one of the beams did not indicate any likelihood of the cable duct lying closer than

40 mm to the external surface. In view of these reasons, in the present case, damage to concrete during the grouting operation was considered only a remote possibility. With elimination of these two from the list of potential causes, further attention was given to study the effect of expansion of grout mix inside the cable duct.

VOLUME EXPANSION IN GROUT

References to expansion of grout in prestressing cable resulting in cracking of the surrounding concrete are available in the literature (2). This phenomenon was observed in some cases when the grouting operations were carried out in sub-freezing temperatures. Free moisture available due to bleeding of the grout mix froze and the resulting increase in volume caused cracking of the surrounding concrete. Such a phenomenon is not relevant in the present case as the ambient temperature at the site never dipped below 20^{o} C. Increase in the volume of grout, after it has set, can take place due to delayed reaction as in the case of under burnt lime present in the cement used for grouting or due to ASR in the grout mix. To safeguard against the harmful expansion caused by under burnt lime, National Codes stipulate testing of cements for expansion characteristics and require compliance to prescribed upper limits. Cement manufacturers, on their part, regularly monitor this parameter and enforce strict control on the expansion characteristics. In view of this, it was taken that a cement having such a deficiency would not have been used in such a major construction.

To identify the occurrence of ASR, the general approach would have been to look for the diagnostic features associated with it. In the present case, drawing of samples from the grout was clearly ruled out because of the apprehension that the prestressing cables might get damaged during sampling. However, a proposal to load test one of the affected beams to destruction is under consideration and in the event of such a testing, samples of the grout material would be made available for testing and analysis. As the load testing would take some time, corroborative evidences on occurrence of ASR were sought and documented. These included: (i) analysis of cracking of PSC beam due to expansive pressure developed within the cable ducts, (ii) availability of moisture within the cable duct, and (iii) composition of the grout mix.

Cracking of PSC Beams.

The crack initiation process in the hardened concrete of PSC beams due to expansive pressures developed within the cable ducts was simulated using two-dimensional finite element modelling technique. The bottom flange of PSC beam was assumed to be composed of triangular elements and an elastic analysis was carried out to study the strain pattern. Cracking of concrete was assumed to initiate at the strain level of 100 x 10^{-6} and it did not necessarily correspond with the maximum stress point. Following observations emerged from this analysis:

1) When the expansion pressure reached a level of 1.5 N/mm^2, vertical cracks initiated along the centre line of the bottom flange (Fig.3.a).

2) Vertical cracks were initiated just below the bottom line of cables when the expansion pressure was about 1.8 N/mm^2 (Fig.3.b).

3) Further increase in pressure initiated horizontal cracks to originate from the bottom line of cables (Fig.3.c).

4) As the expansion pressure reached a level of 5 N/mm^2, horizontal cracks developed from the top cable (Fig.3.d).

As the cracks progress further, they would eventually reach the external surface and the probable locations where they would manifest on the outer surface are shown in Fig.3.d. A comparison of manifestation of cracking as predicted by the theoretical analysis with the field mapping of cracks (Fig.2) indicated a good agreement. Thus, this analysis provided a corroborative evidence in linking the external symptoms to the expansive pressures within the cable ducts.

Seno and Kobayashi (3) have reported laboratory investigations on monitoring expansive pressures caused due to ASR. The mortar specimen containing reactive aggregates were kept confined within sealed metal tubes and strains measured on the surface of the metal tubes were monitored to determine expansive pressures. The maximum expansive pressure logged was of the order of 12 N/mm^2 in a period of 26 weeks. As against this, the pressure required to initiate cracking in the beams was only about 1.5 N/mm^2.

Examination of Crack Features.

To study the crack features, a number of cores were extracted from the bottom flange. One such core extracted from the vertical surface of the bottom flange of the PSC beams is shown in Fig.4. The cracks were observed to be extending beyond the concrete cover and the orientation was indicative of delamination of bottom flange. Relationship between the width and the extension of cracks is shown in Fig.5. As can be seen therefrom, the width almost remained constant as the cracks extended into the hardened concrete. Examination of the cut surface of the concrete showed that the cracks were almost reaching to the position of the prestressing cables. The fractured surface was observed to pass through the aggregates, pointing to the fact that the cracking had occurred only after the binding mortar had matured and gained strength. An examination of the crack features indicated that the nature of associated stress field was direct tension. Such a stress field would not develop due to the action of normal design loads. Whereas, it could be closely linked to the splitting of concrete caused by expansive pressures developed within the cable ducts.

Composition of Grout.

The grout is usually a mixture of portland cement of medium fineness, water and additives. In cases where the ducts are shorter with smooth curves and where more space is available, very fine sand is added. To achieve a flowing consistency, a water-cement ratio of 0.45 is adopted. Additives are added to compensate for the shrinkage in grout mix and in such cases, care is taken to achieve volume stability in the hardened grout. A typical mix as suggested by Guyon (4) would be 12 kg of portland cement, 3 kg of sand, 6 litres of water and 0.36 kg of additives. Thus the composition of the grout is mostly of cement and contains a very high cement content compared to normal concrete. Consequently, the alkali concentration was also expected to be high and above that generally believed to be necessary for a damaging ASR expansion to occur.

Environment within Cable Ducts.

Even after the hardening of grout, a substantial amount of mix water is available as free water and it remains entrapped inside the cable ducts. As these ducts are like sealed tubes, the process of diffusion and drying out does not take place and in all probability, they would remain moist. The PSC beams are located in a region which has an average ambient day time temperature ranging from 20° C in winter to 40° C in summer. As the beams are relatively thinner members, direct exposure to sunshine is likely to raise the temperature level of the grout mix. From these two accounts, it could be stated that the environment within the cable duct would be conducive for ASR to occur and the moisture available within the cable duct and the possibility of higher temperature in the surrounding concrete would sustain such a reaction.

STRUCTURAL APPRAISAL

Vertical stirrups and closed links provided in the cross section of the PSC beams would be normally sufficient to ensure structural integrity of the beams. But, due to expansive pressures inside the cable ducts, additional forces would be generated in the stirrups and links, and at a certain level of expansion, the steel might yield or weaken the anchorage. Well anchored 3-dimensional cage detailing, such as the one provided in the end blocks, would offer good restraint and mitigate to some extent the effect of expansion. Whereas in the sections other than the end blocks, the type of detailing is typical of a 2-dimensional cage without any special attention to enhance the anchorage requirements. This was the detailing adopted in the present case also. In such situations the unrestrained expansion might cause yielding of steel and eventually splitting or delamination of concrete in the bottom flange. When extracted cores were examined, such a feature indeed was noticed. However, as the expansive phenomenon was not likely to occur uniformly throughout the cable length, the delamination feature was noticed to be occurring at intervals and not continuous. To that extent the damage to beams was limited.

The effect of delamination of concrete section in the bottom flange would be to alter the sectional properties of the beam. Any change in the sectional properties, in turn would alter the stresses induced under loading as well as the deformation characteristics of the beam. As the cracking in the bottom flange was not continuous nor extensive, it was concluded that the reduction in structural strength, if any, might not become critical. However, yielding of vertical stirrups is likely to reduce the shear capacity and in order to safeguard the beam from sudden collapse, it may be necessary to strengthen it by vertical prestressing.

CONCLUSIONS

The manifestation of cracking observed in the PSC beams investigated may be explained as due to the expansive pressures developed within the prestressing cable ducts. The expansion phenomenon could have been caused by ASR. The reaction may continue for a long period because of the moisture entrapped within the cable ducts. Finite element analysis of the cross-section indicated that the macro-cracking in concrete initiated inside the beam and progressed to the outer surface. The cracking will not only increase the risk of corrosion to prestressing steel, but also altered the sectional properties and thus the stress levels and deformation characteristics of the beam.

ACKNOWLEDGEMENTS

The work described here forms a part of the research programme of the Construction Development Institute, National Council for Cement and Building Materials, and this paper is being published with the permission of the Director General. The authors are grateful to the team members who contributed to this investigation and, in particular, to Shri S K Gulyani who carried out the stress analysis using finite element modelling technique.

REFERENCES

1. Libby, J.R., 1984, "Modern Prestressed Concrete", Design Principles and Construction Methods, Van Nostrand Reinhold Company, Inc., New York, USA.

2. FIP-CEB Report, 1966, "Practical Recommendations for Design and Construction of Prestressed Concrete Structures", FIP, London.

3. Seno, Y., and Kobayashi, K.,1989, "Expansion Properties of Mortars and Variation in Components of Pore Solutions due to Alkali Aggregate Reaction", 8th Intl. Conf. on Alkali-Aggregate Reaction, Kyoto, Japan.

4. Guyon, Y., 1974, "Lime-state Design of Prestressed Concrete", Applied Science Publishers Ltd, England.

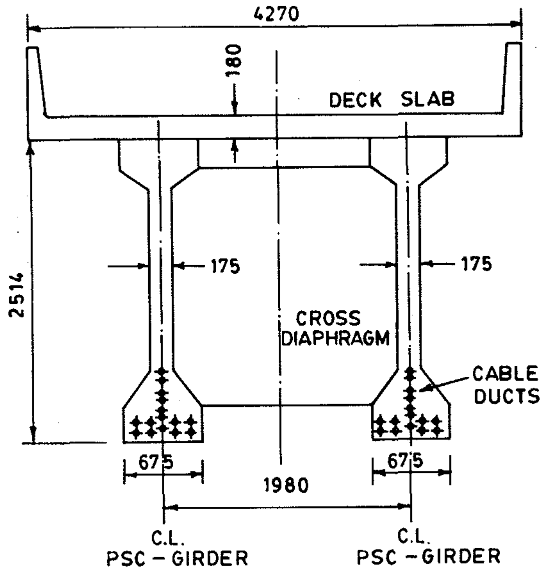

Figure 1 Cross-section of bridge girder, dimensions in mm

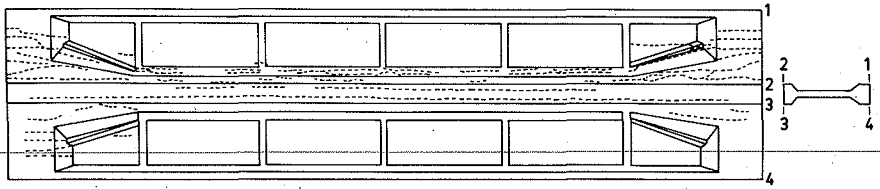

Figure 2 Cracking of PSC beams shown on developed surface

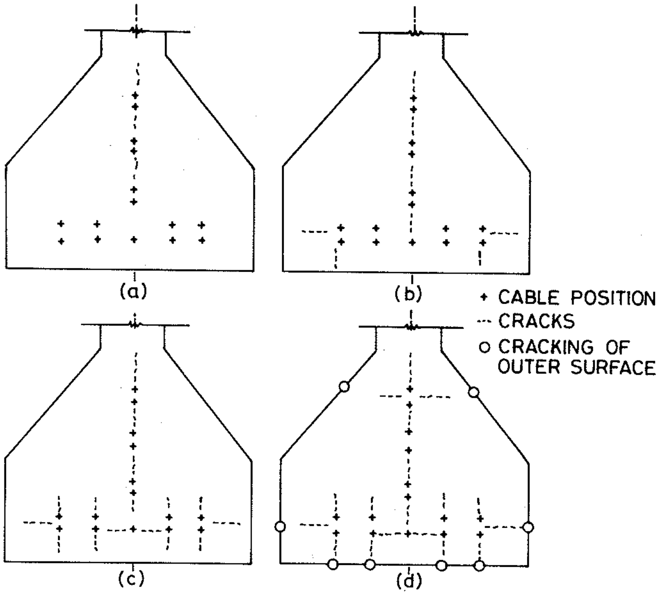

Figure 3 Crack Initiation, predicted by Finite Element Analysis

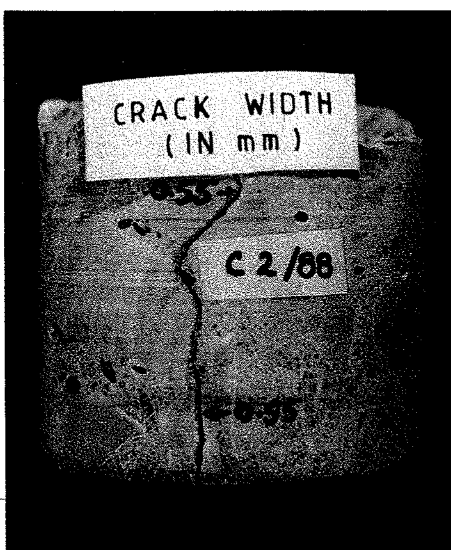

Figure 4 Core extracted from Bottom Flange

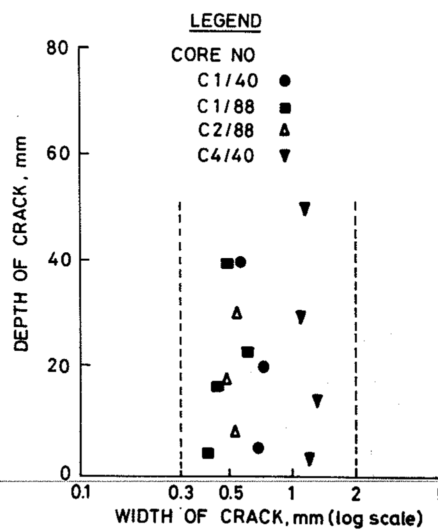

Figure 5 Relationship between crack width and crack depth