Theory and application of the hard inclusion technique for the measurement of *in situ* stresses in prestressed concrete box-girder bridges

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This paper on the hard inclusion technique has generated some concern. This is particularly because the development and manufacture of hard inclusion gauges, or stress gauges, was carried out in my time at both the Mining Engineering Department at Sheffield University and at Stress Engineering Services (now Straininstall Engineering Services) between 1963 and 1980. No reference is made to this work in the paper.

The main difference between the gauges developed at Sheffield University and those described in this paper is merely the method of measuring the strain within the gauge.

At Sheffield University the principle of photo-elasticity was chosen in preference to electrical resistance strain gauges, the main advantage being that photo-elasticity provides effectively the information from an infinite number of strain gauges. Therefore, from a single fringe pattern, it is possible to determine the direction of the principal stress, the magnitude of the principal stress and the magnitude of the minor principal stress.

This technique was used successfully to determine the stress change in rocks, concrete and rubbery material (rocket propellant). However for the determination of *in situ* stress, the greatest problem was the bond between the rigid inclusion and the host material, in the case of this paper, concrete.

Although adhesives have improved in recent years, I would be very surprised if it is possible to create a bond between a rigid material and concrete. The overcored concrete must relax, the inclusion must remain rigid and therefore the interface stresses will be high.

It is reported in the paper that the compressive stresses that were relieved were limited to 2.5 N/mm^2 and the consequential tensile interface stresses will be relatively low. The question then needs to be asked: has this been found to be the maximum compressive stress that can be relieved without a bond failure? If so, the application of the technique in prestressed box-girder bridges will be limited.

At Sheffield University and Stress Engineering Services there

was considerable published work. I include details of three of the papers as follows.

- DHIR R. K. The measurement of *in situ* stresses: the photoelastic borehole stressmeter. *R&D*, 1964, April.
- HAWKES I. and FELLERS G. E. Theory of the determination of the greatest principal stress in a biaxial stress field using photoelastic cylinder inclusions. *International Journal of Rock Mechanics and Mineral Science*, 1969, 6.
- BUSWELL H. J., MOORE D. R. and OWENS A. Solid inclusion stress gauge in composite propellant charges. *Journal of Spacecraft and Rockets*, 1975, 12, No. 8, Aug.

For determining *in situ* stress, the optimum method uses a soft inclusion with the obvious disadvantages which are discussed in the paper.

In the paper's introduction there is a sweeping, and erroneous, statement that the use of the centre hole technique for the determination of the *in situ* load in prestressing tendons cannot be used. The paper states that 'it is nigh on impossible to set up the drilling equipment over a single wire'. In Reference 11 of the paper, the method of carrying out this work was described and at Straininstall we have carried out in excess of 1000 such measurements on single prestressing or post-stressing wires.

A more suitable reference would have been the following.

- OWENS A. *In situ* stress determination used in structural assessment of concrete structures. *Strain*, 1993, Nov.

Author's reply

First of all I would like to thank Dr Owens for taking the time to read my paper and also for the comments he has made and the questions he has framed.

I am not sure what 'concern' my paper on the hard inclusion technique has generated. If Dr Owens is inferring that there is nothing new about the use of hard inclusions to measure stresses in 'rock-like' materials, then I agree, but I do not understand why that should cause concern. Indeed, some of the principles employed in the research I undertook have their

roots in the field of mining engineering, particularly in South Africa where the idea was first developed initially for *monitoring* stresses and latterly for *measuring in situ* stresses.¹⁹ What I have done is to take up the basic idea and to develop a stressmeter for use in concrete structures.

It is misleading to say that the only difference between the work mentioned by Dr Owens and the work carried out at Surrey University is 'merely' the method of measuring strain. Roberts *et al.*²⁰ reported that the monitoring of stresses in the concrete of tunnel linings using a *photo-elastic* stressmeter met with limited success and was subsequently abandoned.

I would be interested to know what happened to the photo-elastic device developed by Dr Owens. The strain gauge rosettes employed in the steel inclusion are well proven and reliable. Also, the inclusion can measure stresses at several (typically 5) locations within the depth of a structural member, and is not limited to surface measurements, the interpretation of which are bedevilled by the unknown level of shrinkage stresses. The hard inclusion can get below the critical 50–100 mm of concrete to levels where the shrinkage effects are minimal.

A strain gauge rosette provides all of the data necessary to measure both the directions and values of the principal stresses, so in that respect photo-elasticity methods offer no advantage.

Bond between the host material and the inclusion can be a problem and we did detect what we thought was bond failure in some specimens, but later concluded that it was localised failure of the concrete. Even in those cases, because of the very localised nature of the breakdown, the expected results were different by only a few per cent.

The interface stresses (apart from the level of stress being measured) are dependent primarily on the ratio of the Young's moduli of the host concrete: adhesive: inclusion. As stated in the previous paragraph, we experienced no major difficulties in that area. Two of the test specimens were broken open after testing and there was no evidence of any breakdown of bond between either the concrete/adhesive or the adhesive/inclusion interfaces. Further research is planned, however, and one of the areas of work will be to try and discover the combination of adhesive/inclusion materials that minimises the interface stresses.

The information I have is that the vast majority of the stress levels measured in the field using other techniques lie between 0 and 5 N/mm², with a considerably smaller number falling in

the 5–9 N/mm². I reiterate that the interpretation of these stresses is open to considerable debate because of the unknown shrinkage stress levels.

I note the references listed by Dr Owens and I look forward to reading them with interest. However I would like to refer him to the papers by Roberts *et al.*^{20,21} which show that the photo-elastic method of measuring stresses has considerable drawbacks. The use of photo-elastic methods is very limited in the fields of civil and structural engineering. The problems associated with bonding the photo-elastic coating on damp concrete surfaces and differences in the thermal coefficients between the photo-elastic gauge and the concrete can give rise to erroneous results. Photo-elasticity is ideal for use in the laboratory but on site the photo-stress method has to be employed, which involves the reflection of polarised light and the consequent loss in intensity.

I am not sure that the use of soft inclusion is the 'optimum' (best) method. It involves a lot of very careful preparation which is both costly and time consuming and, because of its sensitivity to the value of Young's Modulus and Poisson's ratio is unreliable.

Perhaps the phrase 'nigh on impossible' was inappropriate but I think that Dr Owens would concede that a considerable amount of setting up work has to be carried out in order to successfully implement the method *on site*, where first of all a 300 mm diameter hole has to be drilled down to expose the prestressing duct. The duct then has to be cut open and grout removed to reveal a prestressing wire. The wire then has to be cleaned and a rosette adhered to the steel. Then comes the tricky operation of lining up the tiny 1.5 mm diameter drill bit, securing the drill in place and, finally, drilling to a depth of about 1 mm. A database of wire data is then needed to separate out the 'locked-in' stresses in the wires from the induced stresses.

REFERENCES

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