The Application of Fracture Mechanics to Prestressed Concrete Pressure Vessels

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SYNOPSIS

A fracture mechanics approach has been adopted to predict the extent of cracking in a prestressed concrete pressure vessel subject to overpressure. It is concluded that this approach should prove a useful tool in prestressed concrete pressure vessel assessment.

1. INTRODUCTION

In order to examine theoretically the structural behaviour of prestressed concrete pressure vessels under all loading conditions a concrete failure criterion is required. The almost universal availability of computers enables engineers to calculate the stresses sustained by any continua; previously only relatively crude assessments could be made. Now any structure's theoretical time independent and time dependent behaviour can be predicted. However, when the theoretical stresses have been determined it must still be shown that the structure will remain intact throughout the design life. Consequently multi-axial failure stress surfaces have been derived for a variety of materials from the experimental data reported in the literature. Clearly a comparison of the computed stresses with the appropriate failure stresses reveals whether or not the material will fail at the point considered. However difficulty is immediately encountered in theoretical assessments when the failure is allowed to manifest as a crack in the structure; the limitations of the nodal stresses computed at the crack tip by finite elements, for example, are well understood.

Tensile fracture of concrete, whether or not it contains a large crack, occurs in a brittle manner. As noted by Glucklich(1) failure can occur by fracture of the cement paste, fracture of the aggregate, and failure of the bond between the aggregate and the cement paste. Although concrete is not a uniform linear elastic isotropic material, it appears that linear elastic fracture mechanics may be applicable to the fracture of a concrete structure containing a major crack. A number of investigators have measured pseudo-fracture toughness values for a variety of concretes, mortars, and cement pastes[2,3,4,5], generally using artificially cracked beams. For mortars the pseudo fracture toughnesses were between 0.22 and 0.73 ksi $in^{\frac{1}{2}}$. The values for various concretes were very similar. Tests of 1 in. thick compact tension test-pieces cast from mortar carried out by the authors produced fracture toughnesses between 0.29 and 0.43 ksi $in^{\frac{1}{2}}$ - values in excellent agreement with the beam data.

Other fracture criteria for cracked concrete have been proposed by Davidson[5] and Shah and McGarry[6]. The former suggested that fracture occurred when the included angle of the crack in a bend specimen exceeded 10^{-3} radian. It is difficult to see how the angle hypothesis could be applied to other geometries, e.g. a centre cracked plate under tension, where the included angle varies from 0 on the axis of symmetry to π at the crack tip. Shah and McGarry[6] concluded that net section stress was the fracture criterion for cracked concretes and mortars, at least for cracks up to a few inches long. For longer cracks, and for cracks in cement paste, they concluded that a fracture mechanics approach might be applicable. Despite certain doubts, the present authors consider that the pseudo fracture toughness approach to be the most suitable for predicting fracture of concretes and mortars in cases where large cracks or crack-like defects exist.

2. THE APPLICATION OF FRACTURE MECHANICS TO AN OVERPRESSURE TEST OF A PRESTRESSED CONCRETE PRESSURE VESSEL, P.C.P.V.

When a P.C.P.V. is to be subjected to overpressure, it is necessary to establish whether it will cause any deleterious effects on the structural integrity of the P.C.P.V. To illustrate how both pseudo

fracture toughness and crack closure work concepts[7] can be applied for this type of evaluation, the effect of overpressure on an under prestressed P.C.P.V. has been evaluated. The assumed loadings of the vessel are simply prestress and pressure. Initially the stresses in the uncracked top half of the P.C.P.V. were evaluated with the BERSAFE[8] finite element computer program, which has an element decoupling facility. As would be expected, the highest tensile stress occurred at the inner top corner of the P.C.P.V. This stress exceeded the accepted multiaxial failure stress level and a crack was assumed to form running from the top corner at an angle of approximately 45° to the vertical (Figure 1). The elements nearest the top corner were therefore decoupled and subsequent analysis established the work required to completely close the crack under the sustained loadings of prestress and pressure. After the crack closure work had been calculated (Figure 1) the corresponding stress intensity factor was derived (Figure 2). When the calculated stress intensity factor exceeded 0.7 ksi $in^{\frac{1}{2}}$, taken as the material's fracture toughness, further elements were decoupled and the procedure repeated.

Figure 1 shows both the crack closure work and the work required merely to close the crack at the top corner. The difference in these results indicates the work that would be required should the corner bar (which is neglected in these analyses) prevent an open crack in the vessel. Figure 2 presents the stress intensity factors for an open and a closed crack. It can be concluded from Figure 2 that even if the corner bar prevents an open crack in the vessel, the crack should still extend radially from the corner a distance in excess of 8 ft. It must be emphasised that this work assumed that the crack could not transmit shear and that the integrity of the liner was not impaired by the overpressure (and thus there was never any gas in the crack).

The example presented above illustrates how pseudo fracture toughness and crack closure work concepts can be applied to assess the approximate effects of overpressure on P.C.P.V. Obviously the extent of any cracking in a vessel is dependent on the value of the pseudo fracture toughness that has been found for the P.C.P.V. concrete. Clearly therefore a knowledge of creep crack propagation and fatigue crack propagation in concrete would also be required if a future P.C.P.V. code required a sophisticated analysis of the service behaviour of concrete pressure vessels.

3. CONCLUSIONS

It has been shown that the pseudo fracture toughness approach can be used for predicting fracture of concrete and mortars where cracks or crack-like defects exist. When combined with the crack closure work concept, the pseudo fracture toughness approach enables the approximate extent of cracking in P.C.P.V.s to be ascertained. The criterion is applicable to ultimate analysis, proof pressure test evaluations and to the examination of the tensile regions generated through stress re-distribution caused by creep.

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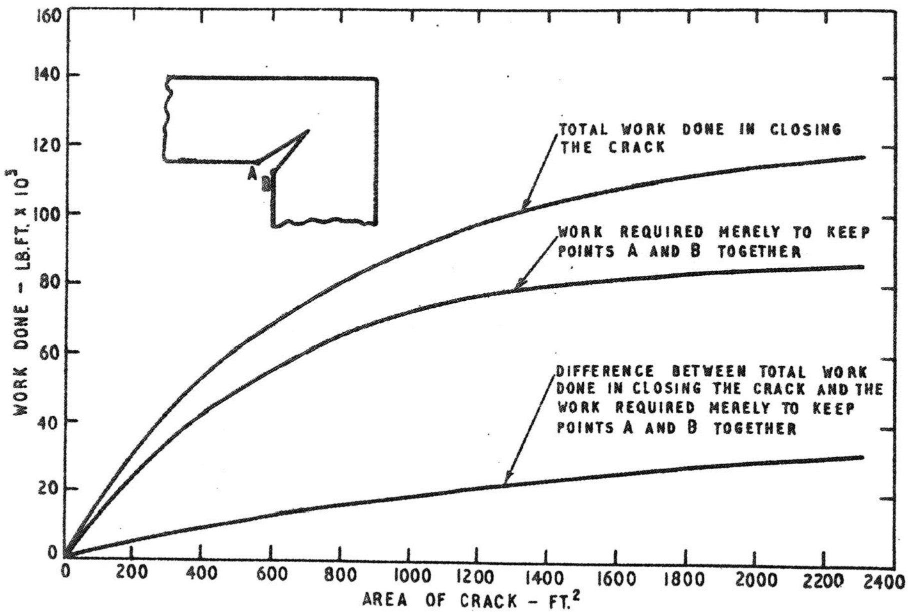

RESULTS OF THE CRACK CLOSURE WORK ANALYSIS OF THE P·C·P·V· UNDER PROOF PRESSURE LOADING.

FIG · 1

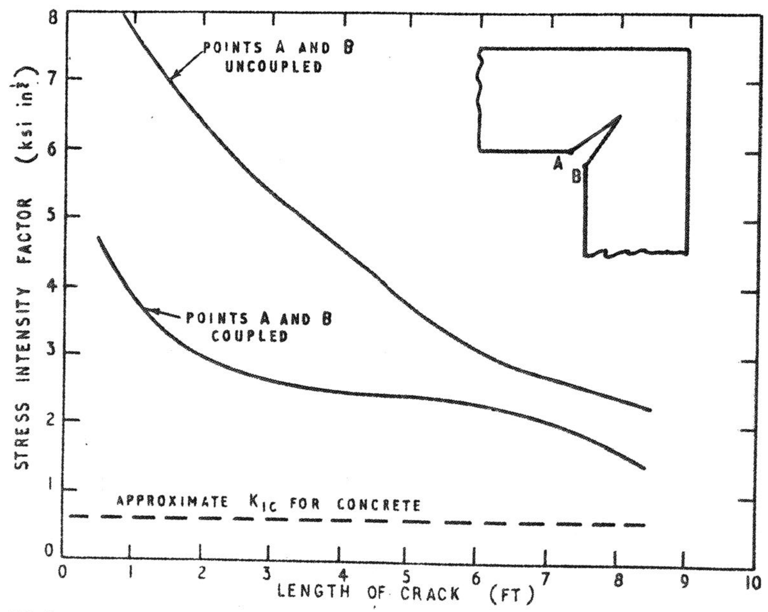

FIG. 2. VARIATION OF STRESS INTENSITY FACTOR WITH CRACK LENGTH.

FIG·2