

CHAPTER VIII – CONCLUSIONS AND RECOMMENDATIONS

Developing a suitable constitutive material model and reliable computational procedure for analysing cracking processes in concrete has been a challenging and demanding task for many researchers worldwide. An analytical method (procedure) for the purpose of establishing a crack constitutive model and implementing the model for the fracture analysis of concrete structures, in particular massive concrete gravity dams under static loading conditions, has been developed, verified and applied in the safety evaluation of a concrete gravity dam subjected mixed-mode fracturing.

The constitutive material crack model, which permits non-orthogonal cracks (originally proposed by de Borst & Nauta 1985), is based on non-linear fracture mechanics (NLFM). A new bilinear tensile softening diagram has been proposed. A shear retention factor that depends on the crack normal strain is also included.

The constitutive material model has been implemented in a finite element (FE) analysis using a smeared crack approach. A sub-program has been specially coded for this research to be incorporated into a commercial, general-purpose FE package called MSC.Marc.

The influence on the cracking behaviour of modelling the strain softening as bilinear or non-linear has been investigated in this study. The concrete used in dams, which in general has a larger aggregate size (as large as 150 mm), a lower cement content and a lower water-cement ratio than normal structural concrete, would require careful investigation of the fracture parameters for the cracking analysis of full-scale concrete dams. The fracture energy G_f of dam concrete would be higher than that of normal concrete. Although the past investigations and experiments indicated huge discrepancies in the fracture energy of dam concrete, $G_f = 100 \sim 300$ N/m could be adopted for concrete in dams where no test results are available. The bilinear softening shape parameters α_1 and α_2 also need to be carefully determined for each particular concrete dam. In this research, $\alpha_1 = 0.25 \sim 0.4$ and $\alpha_2 = 0.05 \sim 0.3$ were studied for their sensitivity in the structural behaviour of concrete dams.

The validity of the proposed cracking model and the computational procedure developed for the purpose of analyzing the tensile fracture behaviour of concrete structures has been confirmed by verification on various concrete structures, including beams and gravity dams, subjected to either mode I or mixed-mode fracturing. All the verification specimens have been experimentally tested or/and numerically simulated before by other researchers.

The crack modelling technique developed has been successfully used in the FE analysis of an existing concrete gravity dam in South Africa and adequately predicted the cracking response of the dam structure under static loadings, including hydrostatic pressure due to overflowing, uplift pressure, silt pressure and seasonal temperature drops in the dam wall. The study has demonstrated the usefulness of NLFM in simulating the concrete cracking process and evaluating the stability of the observed cracks.

The strain-softening model proposed here for concrete could be extended to model other strain-softening materials such as rock, etc. Metallic materials, which normally exhibit a more ductile softening behaviour, could, under “brittle” fracture conditions, also be simulated by carefully calibrating the fracture parameters used in this research.

8.1 Conclusions

The following conclusions are drawn based on the comprehensive fracture modelling of varied concrete structures and the findings arising from the previous chapters:

- Both mode I fracture, which is dominant in the majority of concrete structures, and mode II fracture were modelled successfully.
- The linear softening model is popular because of its simplicity, but fails to predict the true fracture behaviour accurately. The proposed bilinear softening model remains relatively simple to implement, but significantly improves on predicting the softening response of “small-scale” concrete structures.
- For the bilinear softening diagram, the first softening modulus plays a more important (dominant) role when the structure starts to crack. The smaller first softening modulus will provide a stiffer structural response.

- Both plane stress and plane strain crack analyses have been considered and can be confidently adopted in two-dimensional applications.
- The proposed method is mesh objective and could overcome problems such as non-convergence and snap-back.
- The proposed method is element-order objective.
- The crack modelling method developed is able to predict correctly the crack propagation trajectory and the structural behaviour with regard to fracturing in concrete structures. It can therefore be confidently applied in concrete fracture analysis.
- If not considering shear stress concentration near the tip of a crack, constitutive crack analysis normally indicates a higher safety factor and a higher Imminent Failure Flood (IFF) than the classical methods in the analysis of concrete gravity dams for safety evaluation.

Regarding the sensitivity of constitutive fracture parameters to the predicted fracture response of concrete gravity dams, the following conclusions are drawn:

➤ In terms of the cracking propagation profile developed in the concrete dam structures, the following findings are obtained:

- The fracture energy of the concrete G_f has a greater influence on the crack propagation in the lower part of a dam (such as in the vicinity of the concrete/rock interface of Van Ryneveld's Pass Dam discussed in Chapter VII; the greater G_f is, the sooner and deeper the crack will bend into the rock), and less influence on the crack propagation in the upper part of the dam (such as with cracking in Koyna Dam discussed in Chapter VI).
- The influence of the bilinear shape parameters α_1 and α_2 is similar to the general findings for the fracture energy G_f . The value of α_1 does not seem to have much influence, but α_2 with a lower value will make the crack bend downwards into the rock.
- The tensile strength f_t of concrete has a significant effect on the crack trajectory path in a dam. The greater f_t is, the more the crack will bend into the rock.

- The threshold angle also has a large influence on the dam's crack propagation profile, although there no clear trend for this influence.
- The maximum shear retention factor β_{\max} has a large influence on the crack profile in a dam. A smaller value of β_{\max} will cause the crack to bend sooner into the rock foundation.

➤ In terms of the overall structural displacement on the crest of gravity dams, the following findings are obtained:

- The fracture energy G_f normally does not have much influence on the dam's ultimate deformation response.
- The bilinear shape parameters α_1 and α_2 are quite sensitive to the fracture response in normal “small-scale” concrete structures, such as beams, but have only some limited influence on the structural response of large-scale structures, such as concrete gravity dams.
- The tensile strength f_t of concrete has a significant effect on the crack response of a dam. The greater the value of f_t , the less crest deformation there will be in the dam.
- The threshold angle does not have a significant influence on the dam's ultimate deformation behaviour.
- The maximum shear retention factor β_{\max} does not have much influence on the behaviour of a dam.

From all the above findings from the sensitivity study, it can be concluded that the influence of gravity and hydrostatic pressure on a dam are so dominant that the localized fracturing – influenced by the fracture energy G_f , the threshold angle, the maximum shear retention factor β_{\max} and the softening shape parameters α_1 and α_2 – does not affect the structural response significantly. In other words, the effect on the structural response of a concrete dam due to loads, such as self-weight and hydrostatic pressure, etc., is much greater than the effect of the local material fracturing.

8.2 Recommendations

Based on this study, the following recommendations are made for future research on the cracking analysis of concrete structures:

- Water pressure inside cracks could reduce the concrete's resistance to fracturing. Water penetration and uplift pressure inside cracks should be considered.
- Three-dimensional crack analysis of dam structures, in particular of arch dams, is the preferred method of analysis.
- The tensile strength of the concrete and rock should be determined from the tests on the drilled samples taken in situ since the cracking path and the overall response in a dam are very sensitive to the magnitude of the tensile strength.
- The fracture energy of the concrete and foundation rock should also be determined from the tests on the drilled samples taken in situ.
- The bilinear softening parameters α_1 and α_2 should be determined from the data fitting of the experimental non-linear softening curve of the concrete.
- Further research on the influence of the parameters of mode II in the mixed-mode I/II fracture of concrete is recommended.
- A more rigorous definition of the crack blunt width h_c is needed.
- A study on the interaction of cracks with construction joints and foundation contacts could make the prediction of dam safety more accurate.
- The results from the numerical fracture analyses should be combined with field investigations, laboratory testing and common engineering sense to provide a clear overall picture for the evaluation of dam safety.
- The fracture analysis of a dam should be adopted as part of the routine dam safety evaluation by practising engineers for a better and more accurate evaluation of dam safety.
- Constitutive crack modelling is a powerful analysis technique which can be used to supplement the "classical" methods for dam safety analysis.
- In the case of the need for the rehabilitation of "apparently unsafe" dams predicted by classical methods, the fracture analysis method developed can be used to recheck the dam's structural behaviour and its safety, and could lead to a huge saving on unnecessary rehabilitation works.

8.3 Closure

The most challenging areas of this research have been the establishment of the smeared NLFM cracking analysis method and its numerical implementation into a finite element program for the crack safety evaluation of concrete dams. This research shows promise for establishing the ultimate strength of concrete dam structures.