No matter how many instances of white swans we may have observed, this does not justify the conclusion that all swans are white.

Karl Popper (1959)

6 Conclusions

6 CONCLUSIONS

This study set out to test the thesis that *the accuracy of design models for UTCRCP can benefit from the adoption of fracture mechanics concepts.*

The outcomes of the study support this hypothesis.

The support for the main hypothesis is provided through the validation of the three hypothetical propositions of the study. The high performance fibre reinforced concrete was found to be subject to significant size effect. This finding validates the proposition in this regard as discussed in detail Section 6.1. The conclusions with respect to the implications of the size effect are also described in this section. The second proposition states that in contrast to the MOR, fracture mechanics material parameters can be used to accurately and precisely, predict the peak load and importantly, the post-peak flexural behaviour of elements of a different size and geometry. The results from the numerical simulation performed as part of this study support this proposition as discussed in Section 6.2. According to the third proposition, fatigue prediction models for the material can be improved through the use of fracture mechanics. The findings of this study partially support this hypothesis as explained in Section 6.3. The benefits of adaptation of fracture mechanics in design models for UTCRCP are presented in Section 6.4. In the final section of this document recommendations are provided with regards to the implementation of the methods developed in the study.

6.1 Size effect and its implications for design

As part of this study, purposely designed experiments were performed to quantify size effect in the material. The aim was to test the hypothetical proposition posed in Chapter 1 that: *the high performance fibre reinforced concrete material will exhibit a strong size effect due to its high post crack stress capacity. The size effect will limit the reliability of the Modulus of Rupture (MOR) obtained for a specific specimen size and geometry, as a predictor of the peak load of elements of a different size and or geometry.*

Specimens with identical geometry, but of different sizes were tested. The results showed that the material is subject to significant size effect. The main implication is that the nominal maximum tensile stress (σ_{Nu}) obtained for a certain specimen size cannot be used to reliably predict the peak load for a specimen of a different size. The MOR is σ_{Nu} determined in a standardized four point bending beam test on a specimen with fixed dimensions. The cause of the size-effect lies in the assumption of a Linear Elastic (LE) stress distribution at peak load to calculate the MOR. In reality a crack has formed long before the peak load is reached and the material behaviour is highly non-linear. It was shown that if the MOR is used to predict the peak load in the centrally loaded disk using Linear Elastic (LE) analysis, the error of the prediction is in the order of 70 to 100 percent. The conclusion is that because of the size effect the MOR cannot be expected to yield reliable predictions of the bending capacity of a full size pavement. The size effect hypothesis is therefore supported by the findings of this study.

In the conventional pavement design theory used for UTCRCP, the MOR is treated as the strength of the material in bending. The ratio between the MOR and the tensile stress condition in the pavement calculated using LE theory is used to predict the fatigue performance. It is argued that based on the above, the MOR is not the most suitable parameter to be used in the prediction of the performance of pavements under cyclic loading.

The source of the size effect in the MOR parameter lies mainly in the difference in fracture energy release into the crack front for small and large specimens. A non-linear fracture mechanics approach is required to be able to use the parameters from a single sized specimen to reliably predict the flexural behaviour of specimens of different sizes and geometry.

6.2 Characterization of fracture behaviour under monotonic loading

The development of data analysis methods and numerical models to test the second proposition represent a major part of the work performed for this study. The proposition states that *In contrast to the MOR, fracture mechanics material parameters can be used to accurately and precisely, predict the peak load and importantly, the post-peak flexural behaviour of elements of a different size and geometry.*

Methodologies were developed to determine fracture mechanics properties for the high performance fibre reinforced material. The fracture energy (G_f) for the material is determined from notched Three Point Bending (TPB) experiments. TPB tests on fibre reinforced concrete are invariably stopped before the specimen is fully broken. An extrapolation technique was presented that allows the extension of the load displacement curves and determine the full work of fracture (W_f) required to break the beam specimens completely. A best estimate of G_f can be calculated from the W_f values thus obtained.

A close estimate of the tensile strength (f_t) for the material is obtained from an adjusted tensile splitting test procedure. It was shown in this study that f_t for high performance fibre reinforced concrete may be determined from cylinder splitting tests provided that: measures to reduce size effect are observed, the calculation is corrected for the influence of boundary conditions, and the transversal deformation is measured. The test results for fibre reinforced concrete show two separate peak load conditions. Without the measurement of the transversal deformation, the ductile post crack behaviour of the material will obscure the tensile splitting strength. If only the ultimate peak load is recorded, as is generally done, a tensile strength is calculated that is not related to a linear elastic tensile load condition in the sample. Numerical simulation confirmed that the ultimate peak load is related to secondary cracking mechanisms. The first peak represents the linear elastic limit state and from it a best estimate of the tensile strength material property can be calculated.

The tensile splitting methodology for fibre reinforced concrete proposed in this document provides a relatively simple alternative to the more complex direct tensile testing approach. Direct tensile testing yields more detail on the post cracking behaviour of the composite material, but if only a measure of the tensile strength is required, the presented tensile splitting methodology will suffice.

The fracture parameters G_f and f_t form the basis for the development of a fracture mechanics damage model for the material. The f_t value forms the threshold which, if exceeded leads to the formation of a crack. G_f represents the area under the cohesive softening function. This function defines the relationship between the crack width and the crack bridging stress. In an initial attempt to model fracture, a simple exponential shape of the softening curve was used. In the numerical analysis using the embedded discontinuity approach in OpenSees, this shape was found to overestimate the peak load condition for the specimens.

An alternative shape for the softening curve was chosen that better represents the post crack softening behaviour of fibre reinforced concrete. The improved cohesive softening function combines a crack tip singularity with an exponential tail. Four parameters need to be determined to construct the function. The first two are G_f, f_t obtained as described above. The two other parameters define the shape of the singularity and are determined through calibration against the experimental results, i.e.: the crack width (w_I) and the stress (σ_I) at the base of the crack tip singularity.

This cohesive softening function was implemented in both Abaqus and OpenSees finite element software. It was found to provide satisfactory predictions for the fracture response for different specimen sizes, different specimen geometries, i.e. three and four point bending beam specimens, centrally loaded disks and split cylinder tests. In contrast to the MOR, it can be used to extrapolate the parameters obtained for a certain specimen size, to reliably predict the flexural behaviour of specimens with a different size or geometry. This ability of the method to simulate the fracture behaviour of specimens of different sizes and geometries also shows that the calibration of w_I and σ_I is justified. Another advantage of the fracture mechanics approach is that it allows the prediction of non-linear pre- and the post peak flexural behaviour of the material. LE design methods provide a prediction of the peak load condition only.

The numerical simulation of beams containing rebar shows that the models developed in this study can be applied to model the influence of the mesh on the behaviour of UTCRCP.

It is concluded that the findings of the study support the proposition that fracture mechanics parameters can be used to reliably predict the flexural behaviour of the material, whereas the MOR cannot.

It is further concluded that the input required for the definition of the fracture models can be obtained from relatively simple laboratory tests. The fracture energy can be successfully determined from TPB tests using the methodology developed in this study. The tensile strength can be obtained from the adjusted tensile splitting test. It was shown that these methods allow the definition of a softening function that is suitable for the prediction of the flexural behaviour of the UTCRCP material.

6.3 The use of fracture parameters in fatigue life prediction

The last of the propositions of the research states that *the accuracy, and possibly the precision, of fatigue prediction models for the material can be improved through the use of fracture mechanics concepts.*

This proposition is partially supported by the findings of this study. Although the precision of the fatigue life prediction was only nominally improved for the available data, it is argued that fracture mechanics based models are more accurate, because address some of the systematic errors underlying the conventional methods.

The findings of this study showed the limited applicability of LE analysis to the behaviour of the high performance fibre reinforced concrete material. Both of the parameters used as input for conventional fatigue prediction equations, i.e. the maximum tensile stress in the pavement slab and the material strength represented by the MOR, are determined through LE analysis. The numerical analysis performed as part of this study shows that LE analysis of pavement structures may lead to tensile stresses higher than the tensile strength (f_t) of the material. Such stresses cannot exist as they would lead to cracking and stress redistribution. Impossible stresses may be calculated for many design situations since the f_t is generally in the region of 50 % of MOR, which will often be exceeded. The LE assumption underlying the MOR value gives rise to the size effect and disqualifies it as a reliable design parameter as discussed earlier in this chapter.

The fracture mechanics damage models for the material were shown to yield size and geometry independent predictions of the flexural behaviour of the material. By replacing the LE parameters in the fatigue models with parameters determined through fracture mechanics analysis, systematic errors can be eliminated from the predictive equation.

Two fracture mechanics based fatigue prediction models were developed for the material. The first and most promising model requires the ratio between the magnitude of the load at which the cyclic loading is applied and the load at failure of the structural element, as determined through fracture mechanics analysis, as input. This ratio is then used in a statistically calibrated regression equation to predict fatigue life as would be done in the conventional approach. The predictive performance of the model was compared to that of a function calibrated using the conventional approach. Both functions were calibrated against a set of cyclic test results for standard 150 mm x 150 mm beam specimens.

The fracture mechanics peak load model performed slightly better than the conventional model in terms of the prediction of the fatigue life of the centrally loaded disks. Further validation of the method for other mix designs and importantly full scale pavement structures is required.

A second model was developed based on the assumption that the monotonic load-displacement curve provides a suitable envelope for the evolution of the load-displacement response under cyclic testing. This assumption is supported by the comparison of the monotonic and cyclic test data produced as part of this study. An attempt was made to devise a model based on the development of the deflection under cyclic loading. Such an approach can be related to the dissipation of energy in the test. The fatigue data from tests on specimens of different sizes and geometries showed consistency in the amount of energy equivalent dissipated per unit fracture ligament area. Unfortunately the model that was developed performed poorly in terms of the prediction of fatigue.

The fatigue equations developed in this study offer only a limited improvement compared to the conventional approach. The models are based on a mechanistic approach to the prediction of monotonic fracture in the material. This is an important enhancement of the design methodology. The models however, still rely on statistical calibration for the prediction of fatigue fracture propagation. The mechanism of fatigue damage evolution, i.e. the gradual tensile softening of the material with the increase in load cycles is not addressed by the method. A truly mechanistic method that incorporates the softening of the material due to gradual degradation of aggregate interlock and fibre anchorage falls beyond the scope of this study.

6.4 The benefits of the use of fracture mechanics in UTCRCP design

This study has shown that fracture mechanics concepts offer an enhanced description of the fracture behaviour of the high performance fibre reinforced concrete material used in UTCRCP.

The fracture mechanics parameters determined with the methods developed as part of this study are close to true material properties. The use of these parameters will increase the design reliability and decrease uncertainty regarding material specifications. In current practice the MOR tests are sometimes performed on 100 mm x 100 mm beams instead of on beams with a 150 mm x 150 mm cross section. The findings of this study indicate that this would lead to a 10% difference in MOR. Such problems could be remedied through the use of fracture mechanics parameters. The number of tests in the material specifications may also be reduced. Currently the specifications for UTCRCP projects call for both flexural tests on beams to determine the MOR and the centrally loaded disk test to be performed as part of quality control. It has been shown in this study that the performance in the disk test can be predicted from the parameters determined from flexural beam tests, making the disk test redundant.

The determination of fracture mechanics properties during the mix design phase provides additional insight with regards to the fracture toughness of the material. The MOR provides an indication of peak load only, which in addition cannot be reliably generalized beyond the beam specimen for which it was determined. The tensile strength and specific fracture energy can be used to predict the flexural behaviour of a full sized pavement slab and allow optimization of the mix design in terms of fracture softening behaviour.

Fracture mechanics based numerical simulation can be used for the realistic assessment of stresses in the pavement slab. This will assist in identifying the positions where fatigue cracks are likely to develop under different load configurations and how the stresses will redistribute once a crack has formed. Once a crack has been induced, the load response of the damaged slab can be assessed.

The models developed as part of this study can also be applied to predict shrinkage cracking and early age cracking due to warping in concrete pavements. This would require determination of the fracture properties at different ages of the mix. The pavement structure can then be modelled to assess whether the stresses due to warping and shrinkage exceed the tensile strength of the material at a given time.

Fracture mechanics based fatigue equations, even if these are no more precise for certain cases than the conventional approach, should be more accurate. This implies that they may be applied beyond the data set for which they were developed with more confidence than the conventional approach.

These are some ways in which the fracture models developed in this study can enhance the design methods for UTCRCP. Based on the discussion above and in the previous sections, it is concluded that the findings of this work support the thesis that the accuracy of design models for UTCRCP can benefit from the adoption of fracture mechanics concepts.

6.5 Recommendations for implementation and future research

An immediate improvement of current practice can be achieved by replacing the standard tensile splitting test with the adjusted test procedure developed as part of this study. As discussed in Section 6.2, it was shown conclusively by this study that the standard tensile splitting test method does not provide a measurement of the true tensile strength of fibre reinforced concrete material. It is therefore recommended that the adjusted tensile splitting test is adopted into standard practise.

The fatigue behaviour of a single high performance fibre reinforced concrete mix design as used for UTCRCP was investigated as part of this study. Additional testing is required to assess the influence of mix design variables, such as fibre content, on the fatigue performance of the material. A fatigue study including mixes prepared at a range of fibre contents is currently in progress. This will also allow the assessment of the possible link between the values of the f_t and G_f parameters and fatigue performance.

The fracture mechanics based peak load model developed in this study shows some promise for the available fatigue data. It also represents a logical outcome for the findings from monotonic fracture experiments performed on a range of mixes and specimen types as part of this study. A need exists to validate the methodology for different mix types, which will also be possible once the present laboratory study is completed. If the model proves to be accurate for the new datasets, the approach still requires further validation for full size pavement systems before it can be implemented in design methods.

The pavement analysis performed in this study involved a simple load case on a simplified pavement system. Further study is required on the application of the fracture mechanics based method to predict crack patterns under moving loads in combination with loss of support over time, shrinkage and warping stresses, etc.

The models developed in this study can be used to analyse the functioning of the mesh in UTCRCP. This is a topic around which there is considerable uncertainty in the industry at present. The Abaqus models can readily be extended to analyse a UTCRCP structure with different mesh configurations.

The limitations of the LE design assumptions highlighted in this study are relevant to plain concrete pavements as well, though possibly to a lesser extent. It is proposed, that certain findings of the study may be of benefit to design methods for plain concrete pavements.

More results from fatigue experiments that are run up to the applicable range of load applications for long life concrete pavement structures (10^7-10^8) are required to determine whether the power function or logarithmic function should be used in fatigue models.

The models developed in this study provide an opportunity to further investigate the modes of failure of UTCRCP both in past heavy vehicle simulator (HVS) experiments and in the field. A need exists to apply the fracture mechanics models to the full pavement structure to gain further insight in the exact role and optimum configuration of the reinforcement mesh, which is currently a topic of much debate. The fracture mechanics models will allow a more accurate assessment of the formation of damage in the structure.

The development of a truly mechanistic approach to the prediction of fatigue fracture development in concrete pavements is required. It is proposed that only a solid mechanics model that covers the mechanism of fatigue damage evolution through gradual softening of the material under cyclic loading can completely overcome the limitations of current design methods.