Damage and Fracture Mechanics

a) Experimental Investigations into the Fracture Behavior of Cementitious Interfaces

Interfaces between two different mixes or strengths of concrete appear in large concrete structures involving mass concreting such as dams, nuclear containment vessels, cooling towers etc., since joints between successive lifts are inevitable. These joints and interfaces are potential sites for crack formation, leading to weakening of mechanical strength and subsequent failure. Research involving concrete-concrete bi-material interface can provide very useful information in the field of repairs and rehabilitation of concrete structures. As concrete is a heterogeneous material, its fracture behavior is governed by the formation of a fracture process zone (FPZ) which forms ahead of the crack-tip. Due to the formation of FPZ, linear elastic fracture mechanics (LEFM) is not applicable to concrete, and hence the nonlinear fracture mechanics (NLFM) based study becomes essential. Further, in case of a bi-material interface the stress singularities are oscillatory in nature and the fracture behavior of a concrete-concrete bi-material interface is much more complicated. Advanced experimental techniques such as scanning electron microscopy, nano and micro indentation, acoustic emissions and digital image correlations are used for characterizing interfaces between different strengths of concrete with an aim of understanding the fracture processes and determination of the fracture parameters (Figures 4.16 and 4.17).

b) Experimental Studies on Fatigue Behavior of Cementitious Interfaces:

Civil engineering structures such as long-span bridges, offshore structures, airport pavements and gravity dams are frequently subjected to variable-amplitude cyclic loadings. It is well known that fatigue is a process of progressive, permanent internal structural change; however, the mechanism of fatigue in concrete is not clearly understood. Since concrete is a quasi-brittle material with heterogeneous micro structure, the mechanism of fatigue may be quite different from those of metallic materials. Experimental studies are carried out to understand the behavior of plain concrete, reinforced concrete and concrete-concrete interfaces under fatigue loading. The acoustic emission data obtained during fatigue crack propagation are used in the analysis to understand the effect of size on the fracture and fatigue behavior. Material properties are determined for use in analytical models which help in assessment of residual fatigue strength of structures.

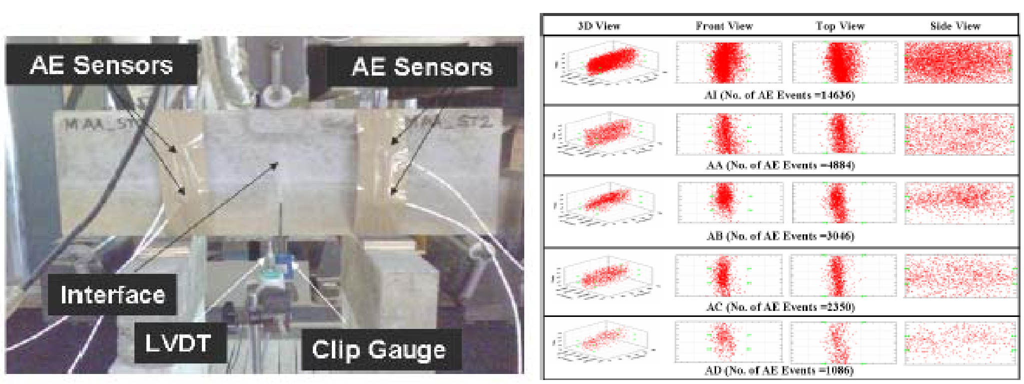

Figure 16: Acoustic emission sensors and results on interface specimens

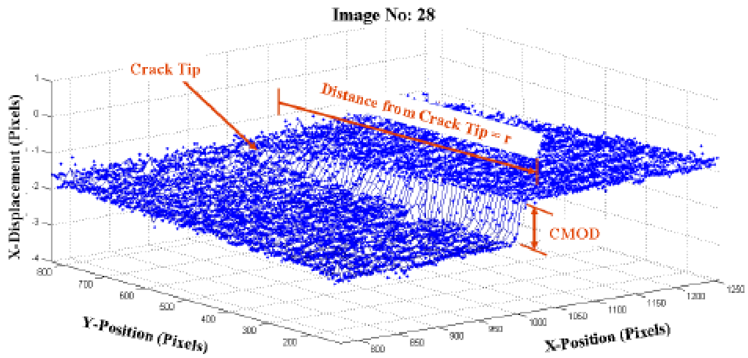

Figure 17: Measurement of crack length and CMOD using DIC

c) Thermal Stress Intensity Factors

Components of turbines, combustion chambers, multi-layered electronic packaging structures and nuclear reactors are subjected to transient thermal loads during their service life. In the presence of a discontinuity like crack or dislocation, the thermal load creates high temperature gradient, which in turn causes the stress intensification at the crack tips. If proper attention is not paid in the design and maintenance of components on this high stress in the vicinity of crack tips, it may lead to instability in the system and decrease in the service life. The concepts of thermal fracture mechanics and its major parameter called transient thermal stress intensity factors can greatly help in the assessment of stability & residual life prediction of such structures. The evaluation of thermal stress intensity factors becomes computationally difficult when the body consists of two different materials or is non-homogenous or made of composites. Studies are performed for development of methods to evaluate fracture parameters for bimaterial interface cracks subjected to mechanical loads and thermal loads using function of complex variables, conservative line integrals and domain integrals. Analytical methods are developed for the computation of thermal weight functions in two dimensional bi-material elastic bodies containing a crack at the interface using the body analogy method and the energy release rate concepts.

d) Correlation Between Damage and Fracture

Damage in concrete members, occur in a distributed zone due to the formation and coalescence of micro-cracks, and this can easily be described through a local damage approach. During subsequent loading cycles, this distributed zone of micro-cracks gets transformed into a major crack, introducing a discrete discontinuity in the member. At this stage, concepts of fracture mechanics could be used to describe the behavior of the structural member. An approach is developed to correlate fracture and damage mechanics through energy equivalence concepts and to predict the damage scenario in concrete under fatigue loading. The objective is to smoothly move from fracture mechanics theory to damage mechanics theory or vice versa in order to characterize damage. The strength and stiffness reduction due to progressive cracking or increase in damage distribution has been characterized using the available indices such as the strength reduction and stiffness reduction factors. It is seen through numerical examples, that the strength and stiffness drop indices using fracture and damage mechanics theory agrees well with each other. It is observed, that through the energy approach a discrete crack may be modeled as an equivalent damage zone, wherein both correspond to the same energy loss.

e) Fatigue and Fracture Behavior of Plain Concrete

It is well known to engineers that fatigue accounts for majority of material failures. Fatigue failure is characterized by a slow but steady crack propagation in the weaker section of structural components due to the action of cyclic loads. In case of metals and ceramics, fatigue fracture has been studied extensively but for concrete, however, the knowledge of fatigue fracture is limited. This is due to the fact that the fracture behavior in concrete is more complicated due to its heterogeneous nature and the presence of large size fracture process zone (FPZ) at the crack tip. It is assumed that under low cycle fatigue loading the decrease in load carrying capacity and stiffness degradation occurs primarily in the FPZ and not in the undamaged material. A fatigue crack propagation law is proposed for plain concrete using the concepts of dimensional analysis, scaling and fracture mechanics. This law considers the effects of tensile strength, fracture toughness, loading ratio and most importantly the structural size. A relationship is obtained between the above parameters using the principles of self-similarity. The proposed law is validated with the experimental results of different investigators that are available in the literature. Furthermore, a sensitivity analysis is done to determine which of the parameters considered are sensitive to fatigue crack growth in concrete.

f) Fracture of Cementitious and Other Composites

Fracture mechanics of concrete is relatively a new area of research and research in this area is going on from as early as mid 1980's. In the recent past during the last 3 years several important findings have been published. Size effect has been confirmed to exist in several types of concrete like high strength and high performance concrete with additives like silica flume and fly-ash and also self consolidating concrete. ANN for predicting the material properties of SCC has been developed. A simple analytical model has been proposed to model the softening and to obtain fracture energy of any type of concrete. Higher order beam theories have been extended to Mode II fracture of layered composites. Fictitious crack model is applied to randomly oriented cracks and also fractal cracks. Probabilistic methods are extended to obtain the most probable fractal dimension. It has been extended to explain the influence of aggregate size on the size effect as well as fracture energy of quasi-brittle materials. Concept of fractals as well as singular fractal functions has been applied to obtain the constitutive laws of concrete. Lattice model via fractals has been proposed to model the heterogeneity of concrete. A 3 D Lattice model is attempted to obtain the shape of the fracture process zone in 3D. Tools for identification of smeared damage have been developed. Both forward and inverse procedures have been formed. Curvature mode shapes via wavelets, simple perturbation on the eigenvalues, ANN through radial basis function network; and iso-eigen value change contours have been developed. Damage indices for seismic damage have been obtained. b-value analysis for concrete and its variation with the properties of concrete with the help of AE facilities has been done. b value has been related to the state of damage in a concrete beam. Fracture energy is related to the AE energy which could in future be used as a tool to identify damage in concrete structures. Moment-tensor method has also been employed to identify possible micro and nano level cracks.

The effect of boundary on the shape of the fracture process zone and hence fracture energy has been validated by observing the decaying of the AE events towards the boundary. A new method to obtain size independent fracture energy is proposed. Multi scale modeling of the fracture process zone via molecular dynamics is in progress. It is proposed to relate a micro lattice model with the molecular dynamics model. Extensive tests on large concrete beams of depths equal to 750 mm both notched and unnotched have been done to obtain reliable values of size independent fracture energy. Damage caused by corrosion and its effect on the durability and remaining life of reinforced concrete have been analysed using a combined fuzzy and probabilistic method. Brunswikian method has been applied to obtain performance-based remaining life.

g) Continuum Damage Mechanics [CDM]

Research has been initiated in the area of CDM with reference to ductile damage modeling. Three isotropic ductile damage models have been developed and integrated with elastoplasticity in the framework of Nonlinear Finite Element Analysis. Effort has also been put to develop efficient computational algorithms; Illustrations have been made to bring out the potential of CDM in structural integrity assessment. Recently, CDM has been further adopted to study failure in FRP composites. As a novel application CDM has also been utilized to generate yield line curve for plates as well as to generate S-N curves under cyclic loading.

Progressive failure of FRP laminates is investigated in the framework of nonlinear Finite Element Analysis using CDM and expressing the failure phenomena through Damage Evolution Models. Damage Models have been developed taking into account coupling of various damage modes of failure in FRP composites. Progressive Failure Analysis (PFA) algorithms have been developed and verified with available bench-mark examples. Further, the algorithms have been extended to Fatigue Failure analysis & S-N Curve generation. The damage-coupled PFA have been illustrated by analyzing various cases of practical importance, such as: Adhesively bonded FRP lap joints, FRP strengthened beams, Yield-line pattern generation as well as PFA of fully composite structural systems.