Fracture Mechanism of Concrete Under Compressive Loads

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It has been well established that concrete subjected to compression undergoes several stages of microcracking prior to failure. However, the actual failure process has been investigated very little. In the following, a description of the failure process of concrete will be given which is based upon observations on concrete specimens, as well as model tests and fracture mechanics studies of the propagation of and the interaction between cracks in a compressive stress field.

The propagation of cracks in concrete subjected to uniaxial compression was observed on the surface of concrete prisms with the aid of a fluorescent ink penetrant (filtered particle method). In order to study interaction of the two major phases in concrete, mortar and coarse aggregates, and their effect upon crack propagation, a thin surface layer was removed from the specimens by sawing. Thus coarse aggregate particles were exposed. The specimens were then loaded continously with a constant strain rate, so that the descending portion of the stress-strain diagram could be observed. At stress levels of 0; 85; 9o and 1oo % of the ultimate load, as well as at various stress levels in the region of the descending portion of the stress-strain diagram, the crack configuration was determined by taking photographs of the concrete surfaces after they had been treated with the penetrant ink. Cracking was evaluated in terms of total crack length per unit area, and average crack spacing. The findings from this study may be summarized as follows:

a) Prior to loading all specimens exhibited some microcracks at the coarse aggregate-mortar interfaces.
b) When the specimens were loaded the cracks started to propagate and new cracks were formed so that the total crack length increased with increasing strain, while the average crack spacing decreased. The changes in crack density and configuration were most pronounced if the specimens were strained beyond their ultimate strength.

c) The load dependent cracks mostly followed the weakest path of the system; however, they showed an orientation which was, as an average, parallel to the direction of the applied load.

d) During the process of crack propagation wider and longer cracks developed by the linking of previously existing microcracks. At failure, large inclined cracks were observed which were the consequence of such a linking process and which occurred in pairs on opposite or adjacent vertical surfaces. The presence of these large cracks at failure suggests that failure resulted from the formation of an inclined failure surface.

The observations of crack growth in concrete were further verified by theoretical studies using fracture mechanics concepts. The major questions to be answered by these studies were as follows:

a) Under which conditions (stress, crack length and crack orientation) and in which direction do cracks tend to propagate in a compression field ?

b) Under which mode does crack extension occur ?

c) Is there a significant interaction between neighboring cracks and is this interaction influenced by the orientation and configuration of cracks ?

In the analysis a model was investigated which consisted of inclined frictional cracks in a homogeneous, isotropic, linearly elastic and two-dimensional infinite body. Here, a frictional crack is understood to be a crack which can transmit forces across as well as parallel to its surfaces.

Crack propagation in such a system was studied by applying Cotterell`s criterion for crack extension which states that a crack will propagate in the direction which maximizes the strain energy released as a result of crack extension.

General solutions for the stress concentrations at the crack tips in a body loaded at infinity by a uniform compressive stress are not readily available. However, the system was modified by transformation of boundary stresses and superposition principles, so that the known solutions for the stress concentrations in a body subjected to pure shear could be used.

Bodies containing single cracks which are inclined at an angle Φ with respect to the applied stress were studied. Also the interaction between two cracks which fall on a common line (collinear cracks) and between overlapping cracks of equal length, and orientation (parallel cracks) were investigated.

The results of the analytical studies may be summarized as follows:

a) Cracks are likely to propagate either in the direction of maximum tensile stress at the crack tip or in the direction of maximum shear stress. The maximum tensile stress occurs at an angle $\theta = -7o^{o}$ with respect to the orientation of the initial crack Φ. The angle θ is independent of Φ. The shear stress is a maximum for $\theta = 0^{o}$. Again this angle θ is independent of the initial crack orientation Φ.

b) The critical orientation of a single crack Φ_{max} i.e. that crack orientation for which a crack will extend at the lowest applied stress was found to depend on the coefficient of friction between two adjacent crack surfaces.

c) In a system with more than one crack, the stress intensity factor K_{II} increases with decreasing distance between the cracks i.e. crack interaction leads to an increase of crack tip stresses.

These analytical studies were further verified by tests on plaster of Paris models subjected to compression. The specimens contained single cracks of various lengths and orientations or collinear or parallel cracks. The results of this study may be summarized as follows:

a) Two modes of crack propagation were observed: branch cracks in the direction of maximum tension i.e. cracks which branched off the main crack at an angle, θ, and shear cracks with an orientation equal to the orientation of the original crack, Φ. For values of Φ equal to 45^{o} or $3o^{o}$ the observed values of θ were lower but close to the calculated value of $\theta = -7o^{o}$ and independent of crack length.

b) The branch cracks propagated in a stable manner. With increasing load the cracks progressively turned towards the direction of the applied load. Shear crack propagation was always unstable and in most cases occurred after considerable branch cracking had taken place.

c) The average stress at initial crack extension was a function of the initial crack orientation and was the smallest for $\Phi = 34^{\circ}$.

d) The stresses at failure decreased with increasing crack length, however, the strength decrease compared to the strength of specimens without cracks was minor.

e) For collinear cracks the tow modes of crack extension (branch cracking and shear cracking) were also observed. In most cases initial branch cracking occurred at the interior crack tips. At higher loads shear cracking often took place resulting in the joining of collinear cracks and failure of the specimen.

f) The failure stresses of specimens with two cracks were considerably lower than the failure stresses of specimens with single cracks. The failure load decreased with decreasing distance between cracks.

The theoretical as well as the experimental studies substantiate the results of the observation of crack propagation in concrete: crack propagation may occur in a stable or in an unstable manner; neighboring cracks accelerate crack propagation and may lead to the formation of continuous failure planes.

Based upon these studies as well as on previous investigations by others the following conceptual model for the fracture of concrete under compressive loads may now be given:

The small cracks which are present in concrete prior to loading are caused by internal stresses due to shrinkage and other volume changes of the cement paste. Under load these cracks start to propagate, at first along the mortar-aggregate interfaces. At stresses close to the ultimate the cracks begin to extend into the mortar. In general the cracks follow the weakest path. However, as an average their orientation approaches the direction of the applied load. The progressive formation of microcracks results in a system composed of a large number of small concrete elements. Failure,

however, does not occur by progressive fracture of individual elements but rather by the interaction of the already existing cracks which propagate, join up to form larger cracks and eventually form one continuous inclined fracture surface. This failure process is conceptually different from the Mohr-Coulomb failure theory which assumes sudden failure to occur along a given plane as soon as a limiting shear stress is reached. A fracture surface is formed whenever a crack becomes critical i.e. when a small load increase will lead to sudden, unstable crack growth. Whether a crack is critical or not depends on its orientation, length and shape as well as on its distance to a neighboring crack. The stress at which a critical crack may form for the first time corresponds to the ultimate strength of concrete. If this stress were kept constant for a short period of time, a failure surface would form. Some time under constant, maximum load is required before a failure surface is formed because of the crack arresting action of aggregates which may be sufficient to momentarily slow down rapid crack growth. If the load is reduced immediately after the ultimate load has been reached spontaneous crack extension can also be slowed down. However, even then the cracks continue to grow at a slower rate thereby causing increased deformation. Thus, when loading concrete into the descending portion of the stress-strain diagram the total crack length will continue to increase. However, by reducing the load the local stresses at the crack tips can be kept just below the value which is critical for a given crack configuration. Thus, the descending portion of the stress-strain diagram corresponds to a continuous sequence of limit states and gives the stress which would cause unstable crack growth and failure surface formation for a given extent of cracking. The larger the strain or the extent of cracking the lower the stress which can cause unstable crack growth.

This study is described in detail in "Fracture mechanisms of concrete under static, sustained, and repeated compressive loads" by S.I.Diaz and H.K.Hilsdorf, Civil Engineering Studies SRS No. 382, University of Illinois, Urbana, Illinois, USA, August 1971