The Experimental Study of Mode – 1 Fracture Parameters of Concrete

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Abstract— Designing structures to avoid fracture is not a new idea. The fact that many structures commissioned by the Pharaohs of ancient Egypt and the Caesars of Rome are still standing is a testimony to the ability of early architects and engineers. In Europe, numerous buildings and bridges constructed during the Renaissance Period are still used for their intended purpose. Fracture mechanics is the science of studying the behavior of progressive crack extension in structures subjected to an applied load. This goes along with the recognition that real structures contain discontinuities which was originated in 1921 by Griffith and was for a long time applied only to metallic structures and ceramics. Concrete structures, on the other hand, have so far been successfully designed and built without any use of fracture mechanics, even though their failure process involves crack propagation. This is not surprising since the proper type of fracture mechanics that takes into account the growth of distributed cracking and its localization into major fractures in concrete structures was unknown until recently. Failures have occurred for many reasons, including uncertainties in the loading or environment, defects in the materials, inadequacies in design, and deficiencies in construction or maintenance. Design against fracture has a technology of its own, and this is a very active area of current research. This module will provide an introduction to an important aspect of this field, since without an understanding of fracture the methods in stress analysis discussed previously would be of little use. The Module on the Dislocation Basis of Yield shows how the strength of structural metals particularly steel can be increased to very high levels by manipulating the microstructure so as to inhibit dislocation motion. Unfortunately, this renders the material increasingly brittle, so that cracks can form and propagate catastrophically with very little warning.

Keywords: Designing structures, Fracture mechanics, inadequacies in design, Dislocation Basis of Yield

I.INTRODUCTION

Fracture mechanics is the science of studying the behavior of progressive crack extension in structures subjected to an applied load. This goes along with the recognition that real structures contain discontinuities which was originated in 1921 by Griffith and was for a long time applied only to metallic structures and ceramics. Concrete structures, on the other hand, have so far been successfully designed and built without any use of fracture mechanics, even though their failure process involves crack propagation. This is not surprising since the proper type of fracture mechanics that takes into account the growth of distributed cracking and its localization into major fractures in concrete structures was unknown until recently

In 1983, the National Bureau of Standards (now the National Institute for Science and Technology) and Battelle Memorial Institute1 estimated the costs for failure due to fracture to be $119 billion dollars per year in 1982. The dollars are important, but the cost of many failures in human life and injury is infinitely more.

Failures have occurred for many reasons, including uncertainties in the loading or environment, defects in the materials, inadequacies in design, and deficiencies in construction or maintenance. Design against fracture has a technology of its own, and this is a very active area of current research. This module will provide an introduction to an important aspect of this field, since without an understanding of fracture the methods in stress analysis discussed previously would be of little use. The Module on the Dislocation Basis of Yield shows how the strength of structural metals particularly steel can be increased to very high levels by manipulating the microstructure so as to inhibit dislocation motion. Unfortunately, this renders the material increasingly brittle, so that cracks can form and propagate catastrophically with very little warning.

1.1) History of Fracture Mechanics:-

Designing structures to avoid fracture is not a new idea. The fact that many structures commissioned by the Pharaohs of ancient Egypt and the Caesars of Rome are still standing is a testimony to the ability of early architects and engineers. In Europe, numerous buildings and bridges constructed during the Renaissance Period are still used for their intended purpose.

The ancient structures that are still standing today obviously represent successful designs. There were undoubtedly many more unsuccessful designs with much shorter life spans. Because knowledge of mechanics was limited prior to the time of Isaac Newton, workable designs were probably achieved largely by trial and error. The Romans supposedly tested each new bridge by requiring the design engineer to stand underneath while chariots drove over it. Such a practice would not only provide an incentive for developing good designs, but would also result in the social equivalent of Darwinian natural selection, where the worst engineers were removed from the profession.

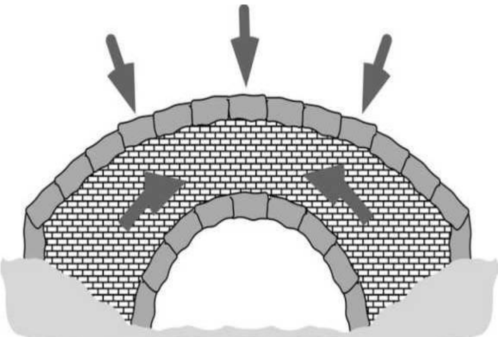


FIGURE 1.1.1 *Schematic Roman bridge design. The arch shape of the bridge causes loads to be transmitted through the structure as compressive stresses.*

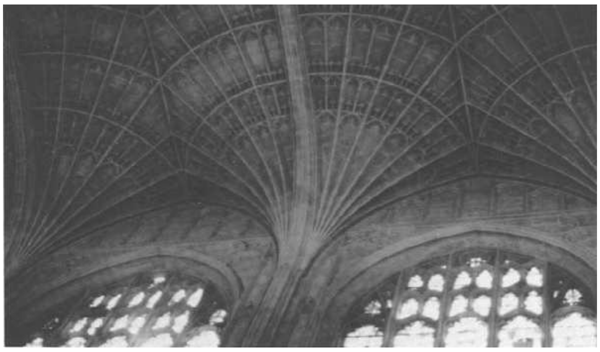


FIGURE 1.1.2 *Kings College Chapel in Cambridge, England. This structure was completed in 1515.*

FIGURE 1.1.3 *The Tower Bridge in London, completed in 1894.Note the modern beam design, made possible by the availability of steel support girders*

1.2.1) Linear Elastic Fracture Mechanics (LEFM):-

Griffith [1921] was the first to develop a method of analysis for the description of fracture in brittle materials. Griffith found that, due to small flaws and cracks, stress concentrations arise under loading, which explains why the theoretical strength is higher than the observed strength of brittle materials. Griffith studied the influence of a sharp crack on an arbitrary body with the thickness t loaded remotely from the crack-tip with an arbitrary load F. see figure 1.2.1.

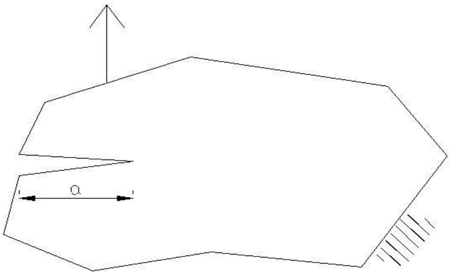


Figure 1.2.1,Arbitrary body with an internal crack of length a subjected to an arbitrary force, F.

By superposition, the potential energy of the body is given by the fracture process in concrete is given in equation 1.2.1

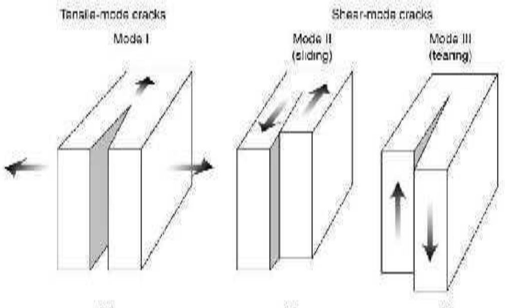


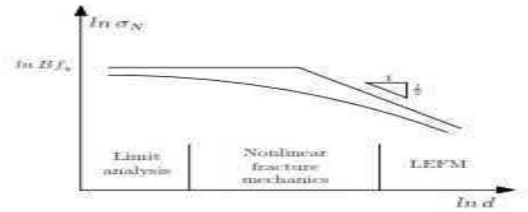
Figure 1.2.2,(a): Crack mode I. (b): Crack mode II. (C): Crack mode III.

1.2.2) Loading models:-

In fracture mechanics a crack can be defined as a separation in material that may occur due to sliding or opening. Such separation is of order of micro structures in material, like in homogeneities. The type of loading conditions that make each of the types of crack are referred to as Mode I for opening and Mode II and III for sliding. In practical situations a loading condition with mixed mode happens while presence of each mode alone is mostly reserved for experimental cases. Figure 1.2.4 shows different loading modes.

1.2.3) Process region:-

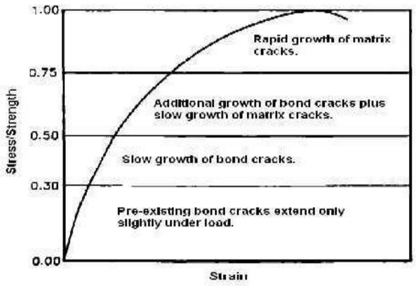
Regardless of size of structure, the whole fracture process takes place in a small region that is near crack edge, called process region. The size of process region compared to dimension of structure or specimen has a big effect on the fracture behavior of the material.



1.3.1) The Fracture process in compression:-

The compressive stress-strain curve for concrete can be divided into four regions, see figure 1.3.1. The figure describes four different states of compressive cracking.

Initial cracks on the micro-level, caused by shrinkage, swelling and bleeding, are observed in the cement paste prior to loading. For loads of approximately 0 - 30 % of the ultimate load the stress-stain curve is approximately linear and no growth of the initial cracks is observed. Between approximately 30 -50 % of the ultimate load a growth in bonding cracks between the cement paste and aggregates is observed. The cement paste and the aggregates have different elastic modulii, which increases the non-linearity of the stress-strain curve. Beyond 50 % of the ultimate load macro-cracks start to slowly form in the mortar, running between the aggregates parallel with the load direction. At app. 75 % of the ultimate load a more complex crack formation is established, where the bonding cracks and the cracks in the mortar coalesce until finally failure occurs .J.P. Ulfkjær [1992]



~~Figure1.3.1. The compressive stress-strain~~ curve for concrete. The curve is divided into four regions for different states of cracking. J.P. Ulfkjær [1992

1.3.2) The Fracture process in tension:-

The tensile strength of concrete is, much like the compressive strength, dependent on the strength of each link in the cracking process, i.e. micro-cracks in the cement paste, meso-cracks in the bond and macro-cracks in the mortar. Consider a concrete rod under pure tensile loading, see figure 1.3.2. The fracture process initiates with crack growth of existing micro cracks at approximately 80 % of the ultimate tensile load. This is followed by formation of new cracks and a halt in formation of others due to stress redistribution and the presence of aggregates in the crack path. These cracks are uniformly distributed throughout the concrete specimen. When the ultimate tensile load is reached, a localized fracture zone will form in which a macro-crack, that splits the specimen in two, will form. The fracture zone develops in the weakest part of the specimen. J.P. Ulfkjær [1992]

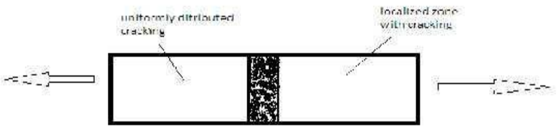


Figure 1.3.2.A concrete rod subjected to pure tensile loading. Outside the fracture zone, the cracks are uniformly distributed. Inside the fracture zone a macro-crack forms which splits the rod in two

3.1) Outline of experimental program

The experimental program was designed to study the stress intensity factor and fracture energy of plain-high strength concrete beams of size 75mm x 75mm x 350mm (Span is 300mm), 75mm x 150mm x 650mm (Span is 600mm) and 75mm x 300mm x 1250mm (Span is 1200mm) with centrically placed notch at mid span of the beam under a three point bending test i.e., with a central point load. The influence of centrically placed notch of specimens on stress intensity and fracture energy was studied on beams of varying sizes with three different mix proportions (M25, M50, and M75).

This experimental program consists of three series of beams for each grade, namely small, medium, and large and having equal notch depth ratio (0.15). Fig 3.2.1 shows the schematic arrangement of the beam specimen subjected to three point bending.

3.2) Materials:-

Cement
Ordinary Portland cement conforming to IS 12269 – 1983 was used for the concrete mix and Specific gravity was found to be 3.5

Fine Aggregate
The fine aggregate (sand) used in the work was obtained from a nearby river course. The fine aggregate that falls in zone –II was used. The specific gravity was found to be 2.60.

Coarse aggregate
Crushed coarse aggregate of 20mm retained was used in the mix. Uniform properties were to be adopted for all the beams for entire work. Specific Gravity of coarse aggregate is 2.78.

Water
Potable water supplied by the college was used in the work
Moulds
Standard cast iron cubes and cylinders moulds were used for casting of cubes and cylinders. Three wooden moulds were prepared for casting of beams of sizes as follows

1. 300*75*75 mm
2. 600*150*75 mm
3. 1200*300*75 mm

Vibrator:
To compact the concrete, a plate vibrator and as well as needle vibrator was used and for compacting the Test

specimens, cubes, cylinders and beams.

Casting:

The moulds were tightly fitted and all the joints were sealed by plaster of Paris in order to prevent leakage of cement slurry through the joints. The inner side of the moulds was thoroughly oiled before going for concreting. The mix proportions were put in miller and thoroughly mixed.

The prepared concrete was placed in the moulds and is compacted using needle& plate vibrators. The same process is adopted for all specimens. After specimens were compacted the top surface is leveled with a trowel.

Curing:

The NSC specimens were removed from the moulds after 24 hours of casting and HSC specimens were removed after 48hours of casting, the specimens were placed in water for curing

Marble Cutter:

The beams were cut with a marble cutter in to the hardened concrete (Fig 3.1).

FIGURE 3.1 cutting beam with marble cutter.

3.3) Test Setup and Testing Procedure:

All the specimens were tested on the Computerized Universal Testing Machine of 1000kN capacity under displacement control at a rate of 0.02mm/min. After 28days of curing the samples were taken out from the curing tank and kept for dry. Then notch is provided at the centre of the beam with notch to depth ratio of 0.15. After this the sample was coated with white wash. One day later the sample was kept for testing

The notched beam specimen was kept on the supports of testing machine as shown in below figure 3.2.1. When performing a test, a gradually increased load is applied to the notched beam until a stress level is reached which results in crack propagation

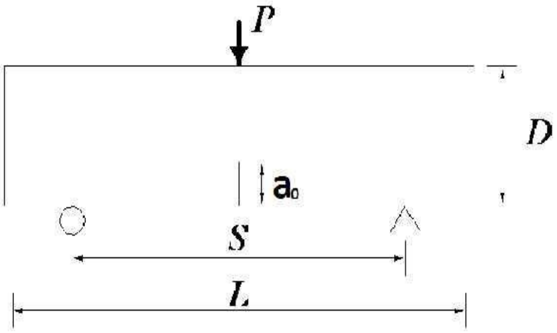


Figure 3.2.1. The Three point bending beam specimen for mode –1 fracture

4.2) Solution of finite element problem by using ANSYS:-

In general, a finite element solution may be broken into the following three stages. This is a general guideline that can be used for setting up any finite element analysis.

1) **Preprocessing**

2) **Solution**

3) **Post processing**

1) **Solution:-**

- Assigning loads: here we specify the loads (point or pressure)
- Constraints: here we specify constraints (translational and rotational)
- Solving: finally solve the resulting set of equations.

3) **Post processing: -** in this stage we can see

- Lists of nodal displacements
- Element forces and moments
- Stress contour diagrams

Table 3: Failure loads, Nominal stresses, Stress Intensity Factors

Concrete grades	Specimen	pmaX	□□ □ □	K_I
		KN	(N/mm^2)	(N/mm^2)□mm
M 25	Small	4.95	5.28	54.93
	Medium	8.65	4.61	67.88
	Large	14.65	3.91	81.29
M 50	Small	5.95	6.35	66.03
	Medium	10.1	5.39	79.25
	Large	16.9	4.51	93.77
M 75	Small	6.85	7.31	76.02
	Medium	11.9	6.35	93.38
	Large	18.6	4.96	103.21

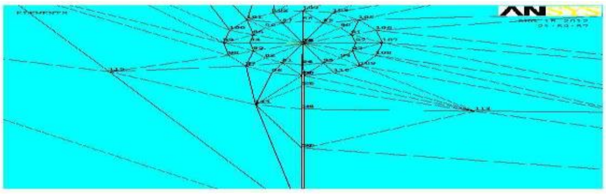


Fig.4.3: mesh at crack tip of the beam in ANSYS

Table 4: Fracture Energy, Brittleness number, Cohesive Fracture Zone length

Concrete grades	Specimen	G_f	□□	C_f
		j/m^2		mm
M 25	Small	383.18	0.37	20.06
	Medium	383.18	0.74	20.06
	Large	383.18	1.49	20.06
M 50	Small	322.89	0.48	15.67
	Medium	322.89	0.95	15.67
	Large	322.89	1.91	15.67
M 75	Small	293.18	0.69	10.81
	Medium	293.18	1.38	10.81
	Large	293.18	2.76	10.81

Discussission

1. The Stress Intensity Factor increases with increase in beam sizes as well as compressive strength of concrete.
2. The Fracture Energy decreases with increase in compressive strength of concrete.
3. The Brittleness number increases with increase in beam sizes as well as compressive strength of concrete

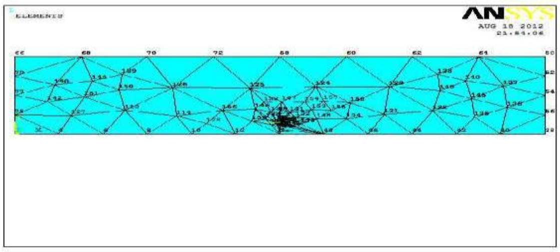


Fig. 4.2 meshing the beam in to small elements in

ANSYS

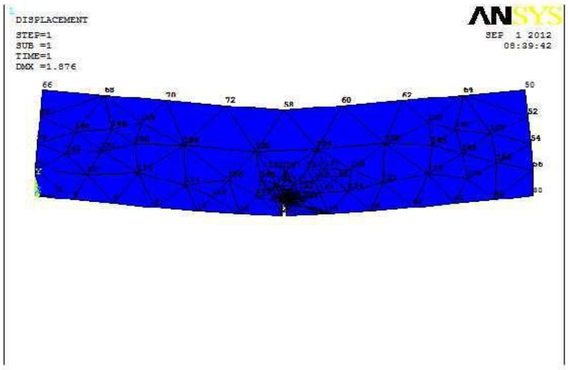


Fig.4.4: deformation of the beam in ANSYS

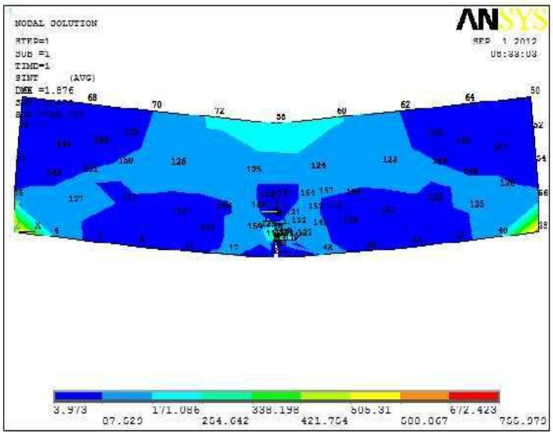


Fig.4.5: stress intensity in the beam in ANSYS

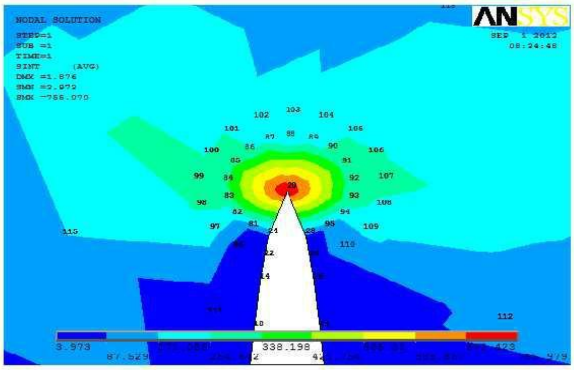


Fig.4.6: stress intensity in the crack tip of the beam in ANSYS

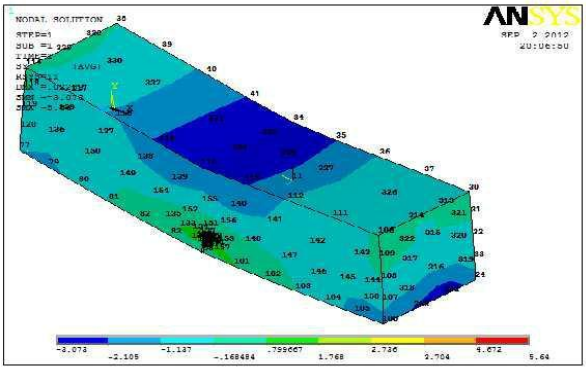


Fig.4.7: 3D of the beam showing failure stresses in ANSYS

M25-Small beam before loading

M25-Small beam after loading

M 50 -Small beam before loading

M 50-Small beam after loading

M 25 - Medium beam before loading

M 75 - Medium beam after loading

Table 5: Failure Stresses (Numerical) Vs Failure Stresses (ANSYS)

Concrete grades	specimen	σ_N	σ_N(ANSYS)
		(N/mm^2)	(N/mm^2)
25	Small	5.28	5.64
	Medium	4.61	4.94
	Large	3.91	4.15
50	Small	6.35	7.12
	Medium	5.39	6.08
	Large	4.51	5.23
75	Small	7.31	8.60
	Medium	6.35	6.87
	Large	4.96	5.45

CONCLUSIONS

It is observed that, failure stresses (nominal stresses) decreases with increasing of beam sizes. It is also observed that, stress intensity factor increases with increase in beam sizes for all grades of concrete. It is also observed that, stress intensity factor increases with increase in compressive strength of beams. It is also observed that, Fracture energy decreases with increase in compressive strength of concrete. It is also observed that, Brittleness number increases with increase in size of the specimen. It is also observed that, Brittleness number increases with increase in compressive strength of the specimen

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