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RESEARCH ARTICLE

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PROPORTION MODE OF CRACK PROPAGATION THROUGH PLAIN CONCRETE

SONTI GIRISH BABU[1], V.ANJANEYA PRASAD[2], M.MALLIKARJUNA RAO[3]

[1]M.Tech, student, Department of Civil Engineering, Chintalapudi Engineering College, Ponnuru, Guntur (D.t), A.P

[2]Professor, Department Civil of Engineering, Chintalapudi Engineering College, Ponnuru, Guntur (D.t), A.P

[3]Assistant Professor, Department of Civil Engineering, Chintalapudi Engineering College, Ponnuru, Guntur (D.t), A.P

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ABSTRACT

A series of studies on application of fracture mechanics to failure of concrete are summarized. Topics discussed in this paper include toughening mechanisms in the fracture process zone of concrete, principles of linear elastic fracture mechanics, various nonlinear fracture models, the determination of material fracture parameters, R-curve approaches, fracture of fiber reinforced concrete and mixed mode and mode I fracture. It is shown that fracture mechanics has now been established as a fundamental approach to describe crack propagation and subsequent failure of concrete structures and failure stresses (normal stresses and shear stresses) decreases with increasing of beam sizes. It is also observed that, stress intensity factor increases with increasing in beam sizes for all grades of concrete.

I. INTRODUCTION

Cementitious constituents can be classified into paste, mortar, and concrete categories. ‘paste is defined as the mixture of cement and water, ‘mortar’ is the mixture of small aggregate, such as sand, with paste, and ‘concrete’ is the composite created with larger aggregate, such as gravel or stones, is mixed with mortar. The cement found in these constituents hydrates when mixed with water, forming a hard matrix after curing. While in a liquid form, however, this paste fills the space among aggregates, both large and small, and bonds them together to form mortar or concrete. In addition, a variety of admixtures are used with concrete to improve global behavior, both wet and dry.

During the curing and hardening phases of the hydration process a loss of moisture occurs in the cement paste, causing shrinkage. Shrinkage is the major cause of weak tensile strengths found in concrete, and is also the cause of many internal flaws and cracks that exist in concrete prior to loading. These flaws govern the mechanical behavior of the global concrete material as the flaws initiate and propagate cracks during the application of stresses. Mechanical responses are influenced by the fracture processes of these flaws under loading.

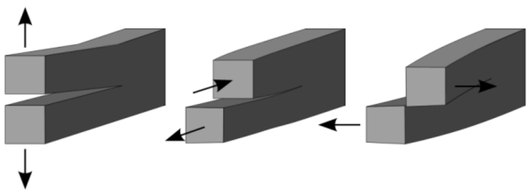
The stress- displacement relationship for concrete subjected to uniaxial tension has been divided into four stages based on initiation and propagation of internal cracks and flaws. The first stage includes all loads less than 30% of the peak load; initiation of internal cracks is negligible during this first stage. The second stage spans all loads from the first stage to less than 80% of the peak load. The internal cracks initiate and propagate during this stage; these cracks are generally isolated and randomly distributed. The third stage includes loads over 80% and up to the peak load. At this point micro cracks and flaws begin to link into large, continuous propagating cracks. This phenomenon is known as strain localization. The large crack propagates only when the large load increases, up until the peak load. At this loading point the crack length is referred to as critical crack length. After the peak load is applied major cracks continue to propagate even though the load may decrease.

1.1 Modes of fracture failure:

There are three modes of fracture failure

1) Mode I
2) Mode II
3) Mode III

Mode I is the opening mode. Mode II is the sliding mode. Mode III causes sliding motion but the displacement is parallel to the crack front causing tearing (which is also called mixed mode).



Four parameters have been well accepted to measure the potency of a crack.

1) Energy release rate (G)
2) Stress intensity factor (K)
3) J- integral (J)
4) Crack tip opening displacement (CTOD)

Energy release rate is energy based and is applied to brittle or less ductile materials. Stress intensity factor is stress based, also developed for brittle or less ductile materials. J- Integral has been developed to deal with ductile material. It formulation is quite general and can be applied to brittle materials also. Crack tip opening displacement is displacement based which was developed for ductile materials.

1.2 Mixed mode crack initiation and crack growth:

For conservative fracture based design estimates, one needs to characterize the crack under mixed mode loading. In mixed mode condition studies are carried out in finding crack extension direction, critical load and stability of crack path. Various modes have been proposed to characterize the mixed mode crack. Essentially, the models have been proposed are based either on energy or stresses.

Mixed mode crack propagation criteria:

Following criteria are,

1) Modified Griffith criterion
2) Maximum tangential stress (MTS) criterion
3) Strain energy density (SED) criterion

In the *modified Griffith criterion*, the concept of energy balance has been extended to include energy release rates associated with all the modes. Total energy release rate for a crack in a plate subjected to mode I and mode II loading is given as, ($G=G_I+G_{II}$). According To This Criterion, crack extension will occur in the direction where energy release rate total is maximum and the extension will take place when the maximum energy release rate reaches a critical value. The critical value depends on the material considered. *Maximum tangential stress criterion* (MTS) was proposed by erdogan and sih based on a criterion component of stress state reaching a critical condition.

According to MTS criterion, crack extension will occur in the direction where tangential stress component $\sigma_{\theta\theta}$ at an infinitesimal radial distance r_0. From the crack tip is maximum and the extension will take place when the maximum tangential stress reaches a critical value which is a materials dependent parameter. Based on energy principles, sih proposed *strain energy density criterion* (SED). According to SED criterion, crack extension will occur in the direction of minimum strain energy density S (θ) and the extension will occur when the S (θ) reaches a critical value S_c which is a material dependent parameter.

2. 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 eccentrically placed notch at (L/4) from mid span of the beam under a three point bending test i.e., with a central point load. The influence of eccentrically placed notch of specimens on stress intensity and fracture energy was studied on beams of varying size effects 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 (0.2) from a distance X. In this series '0.2' represents the notch depth ratios and 'X' represents the position of notch from the center of the beam (L/4). Fig1 shows the schematic arrangement of the beam specimen subjected to three point bending.

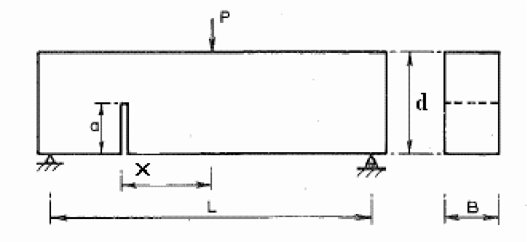


Fig 1: Loading configuration for mixed mode test

2.1. MATERIAL DETAILS

1. Cement

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

2. 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.

3. Coarse aggregate

Crushed coarse aggregate of 4.75mm size passing and 10mm retained proportion and 10 mm passing-20mm retained proportion was used in the mix. Uniform properties were to be adopted for all the prisms for entire work. Specific Gravity of coarse aggregate is 2.78.

4. Admixtures:

To achieve the desired workability CONPLAST SP430 was used as super plasticizer.

5. Water

Potable water supplied by the college was used in the work

6. Moulds

Specially made wooden specimens are used for casting prisms. Standard cast iron cube and cylinder were used for casting of cubes, cylinders.

7. 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 prisms.

8. Marble Cutter:

The beams were cut with a marble cutter in to the hardened concrete (Fig 2.1).

Fig 2.1: cutting a beam with marble cutter

2.2 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.

2.3 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.

3. TEST SETUP AND TESTING PROCEDURE

All the specimens were tested on the universal testing Machine of 1000 kN capacity under displacement control at a rate of 0.15mm/min. After 28days of curing the samples were taken out from the curing tank and kept for dry. After this the sample was coated with white wash. One day later the sample was kept for testing. The beam specimen was kept at the center of testing machine. Beam specimens were put on roller supports exactly under the centre of the load point. For finding the compressive strength of the cube, split tensile strength of the cylinder and the modulus of rupture of the prism specimens were tested on the UTM. The specimen was placed in the machine in such manner that the load was applied on the axis of the specimen was carefully aligned at the center of the loading frame .The load was applied without shock and increased continuously at a constant rate until the resistance of the specimen to the increasing load breaks down and no greater can be sustained .The maximum load applied on the specimen was recorded. A UTM was computerized which was used to measure the deflections under the mid span below the load point.

Table 3.0: Quantities of Materials

GRADE	PROPORTIONS	CEMENT Kg/m^3	F.A Kg/m^3	C.A Kg/m^3	WATER %	S.P Ml/kg
M25	1:1.142:2.56	443.322	506.273	1134.90	0.43	-
M50	1:1.472:3.043	409.207	602.352	1245.216	0.35	37
M75	1:1.2:2	542.98	651.570	1085.96	0.22	37

Fig:3.0 Test Setup

Fig: 3.1 beams before testing (large beams)

Fig: 3.2 beams before testing (medium and small)

4. RESULTS AND DISCUSSIONS

The beam specimens were tested on the Universal Testing Machine under displacement rate control. All the beam specimens were tested under the three point bending under the displacement rate control. A photograph of the test setup is shown in Fig 3.0. To understand the fracture behavior of plain concrete beams the following graphs were drawn, Load Vs Mid span deflection (Fig 4.0, 4.1, 4.2). The normal and shear stress and stress intensity factor and fracture energy of the beams subjected to three point bending with eccentric notch calculated by using the eq.s (5.1 to 5.8) from reference (1) and reported in Table 4.0 and in table 4.1. From the graphs and Tables it was observed that, for mixed-mode failure of concrete, It was found that the stress intensity factor and fracture energy increases with the increasing of beam sizes and decreasing the failure stresses with increasing the beam sizes. The brittleness of the beam increases with increase the size of the beam.

Based on the tests on Concrete beams it can be observed that, in the case of eccentric notched plain concrete beams, the first crack appeared in the tension zone at notch tip. The deflections were measured only up to the ultimate load and failed suddenly in to two pieces.

CALCULATIONS:

$\sigma_n = 6M / (b^2 t(1-\alpha))$ 4.1

$\tau_n = V / (bt (1-\alpha))$ 4.2

$M = \{(p/4) (s-2x)\} + \{(wl/4) (s-2x)\}-\{(w/8)(l-2x)^2\}$4. 3

$V=\{(p/2)+ (wx)\}$ 4.4

$K_I = \sigma_n * \sqrt{b} * \sqrt{(\Pi*\alpha)} * f_I (\alpha)$ 4.5

$K_{II}=\tau_n * b * \sqrt{(\Pi*\alpha)} * f_{II}(\alpha)$ 4.6

$f_I (\alpha) = 0.689$

$f_{II} (\alpha) = 0.530$

$K=\sqrt{(K_I^2+K_{II}^2)}$ 4.7

$G = K^2/E$ 4.8

σ_n = normal stress, τ_n = shear stress, M = bending moment at distance x, V = shear force at distance x, w = wt. per unit length of the beam, p = point load, α = a/b (notch depth to beam depth), s = nominal span, l = length, b = depth, t = thickness, $f_I (\alpha)$ and $f_{II} (\alpha)$ are dimensionless parameters, K_I = stress intensity factor of mode I, K_{II} = stress intensity factor of mode II, K = stress intensity factor for mixed mode, G = fracture energy for mixed mode, E = young's modulus.

Table 4.0: Failure stresses (normal and shear stress)

Specimen designation	Ultimate Load Kn	Normal stress(σ_n) n/mm^2	Shear stress(τ_N) n/mm^2
S-25	06.000	7.447	0.667
M-25	10.150	6.384	0.565
L-25	16.500	6.181	0.461
S-50	6.450	8.037	0.717
M-50	11.150	7.009	0.620
L-50	18.500	6.910	0.516
S-75	06.150	7.660	0.683
M-75	11.000	6.910	0.612
L75	17.000	6.360	0.475

Table 4.1: Stress intensity factors and fracture energy

Specimen designation	Ultimate Load Kn	Stress intensity factor (n/mm^2)m^2	Fracture energy n/mm
S-25	06.000	1.120	0.044
M-25	10.150	1.353	0.064
L-25	16.500	1.851	0.120
S-50	06.450	1.204	0.036
M-50	11.150	1.485	0.054
L-50	18.500	2.070	0.106
S-75	06.150	1.148	0.026
M-75	11.000	1.465	0.043
L-75	17.000	1.906	0.073

Fracture energy for non linear was calculated from formula, from reference (4)

$$G = \frac{U - 0.5mg\delta_0}{1.15bh\left[1-\frac{a_0}{h}\right]/\cos\alpha}$$

Where, U is the area under the load versus vertical deflection curve up to the point of instability

δ0 is the vertical deflection at the instability point.

α is the angle between the vertical plane and the crack plane ao /h is the notch depth ratio.

mg= w= unit weight of the beam

Table 4.2: Fracture Energy for non linear from Formula

Specimen designation	Ultimate load KN	FRACTURE ENERGY($G_{FORMULA}$)n/mm
S-M25	06.000	0.049
M-M25	10.150	0.062
L-M25	16.500	0.052
S-M50	06.450	0.109
M-M50	11.150	0.160
L-M50	18.500	0.113
S-M75	06.150	0.066
M-M75	11.000	0.069
L-M75	17.000	0.074

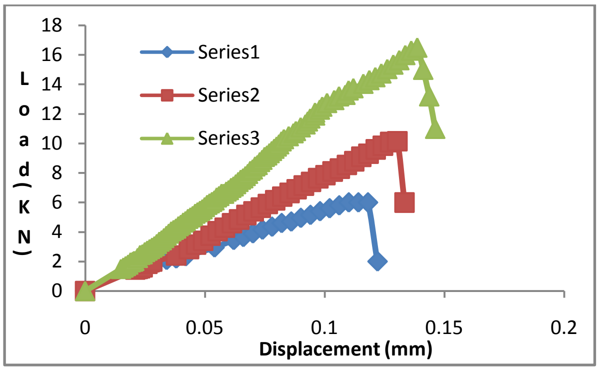


Fig 4.0: Load-Displacement diagrams for M25-Small, Medium, and Large beams

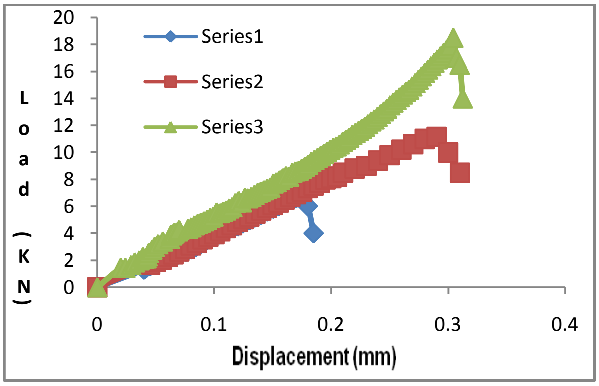


Fig 4.1: Load-Displacement diagrams for M50-Small, Medium, and Large beams

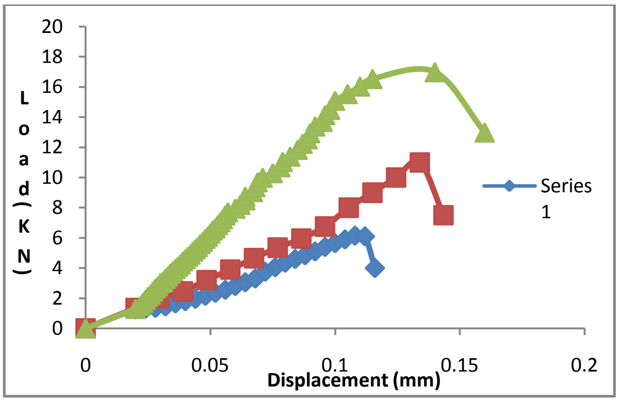
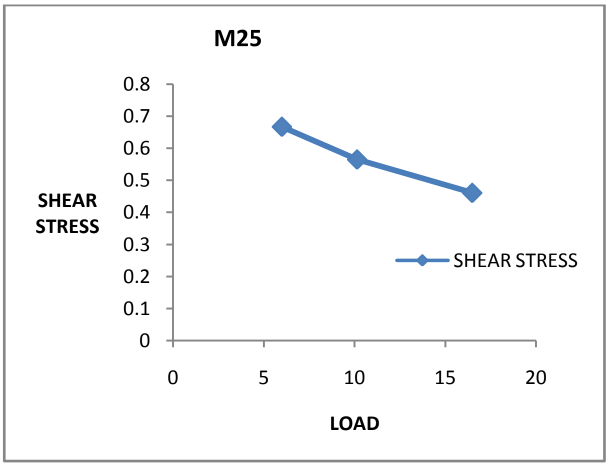
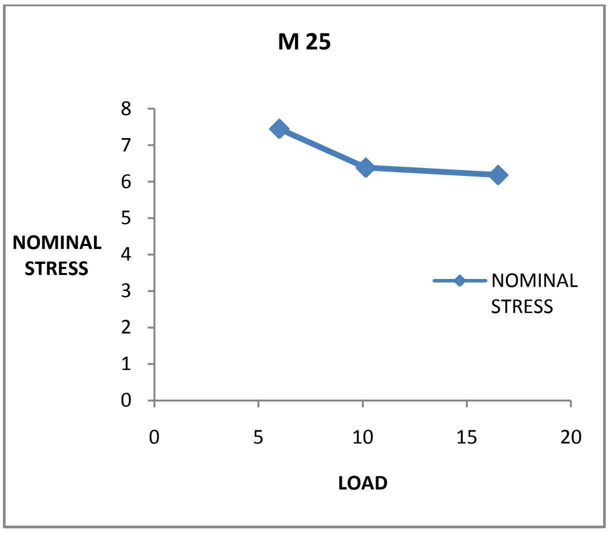
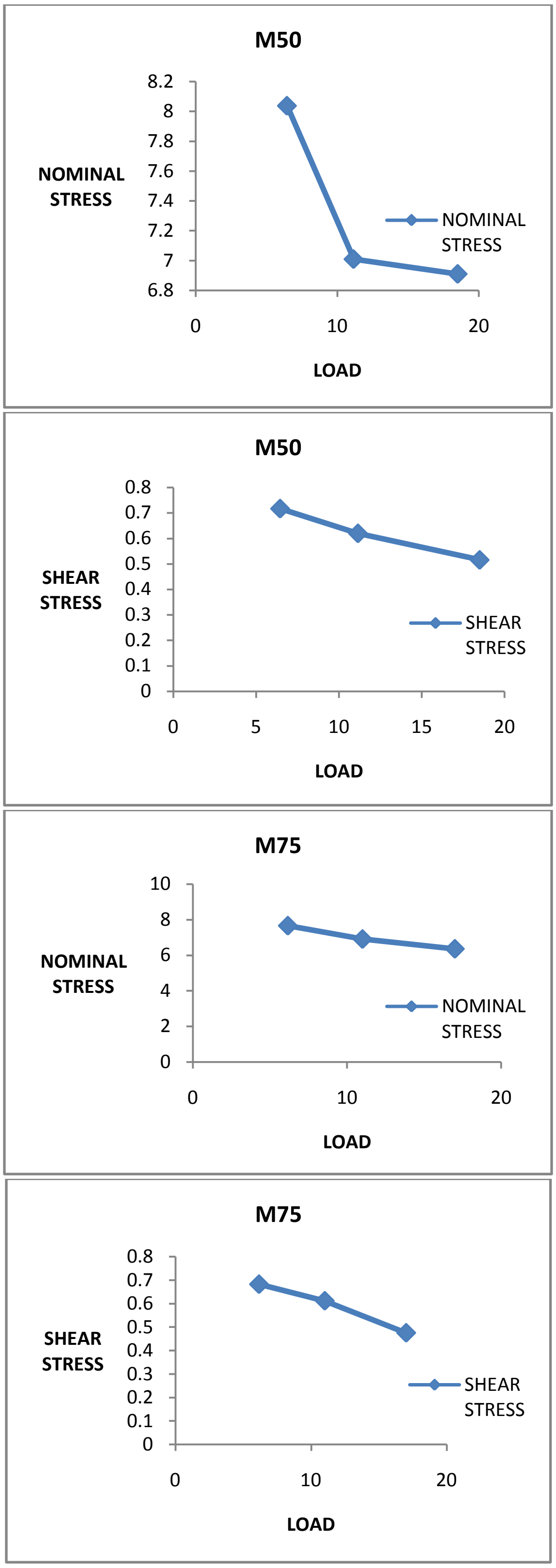


Fig 4.2: Load-Displacement diagrams for M75-Small, Medium, and Large beams







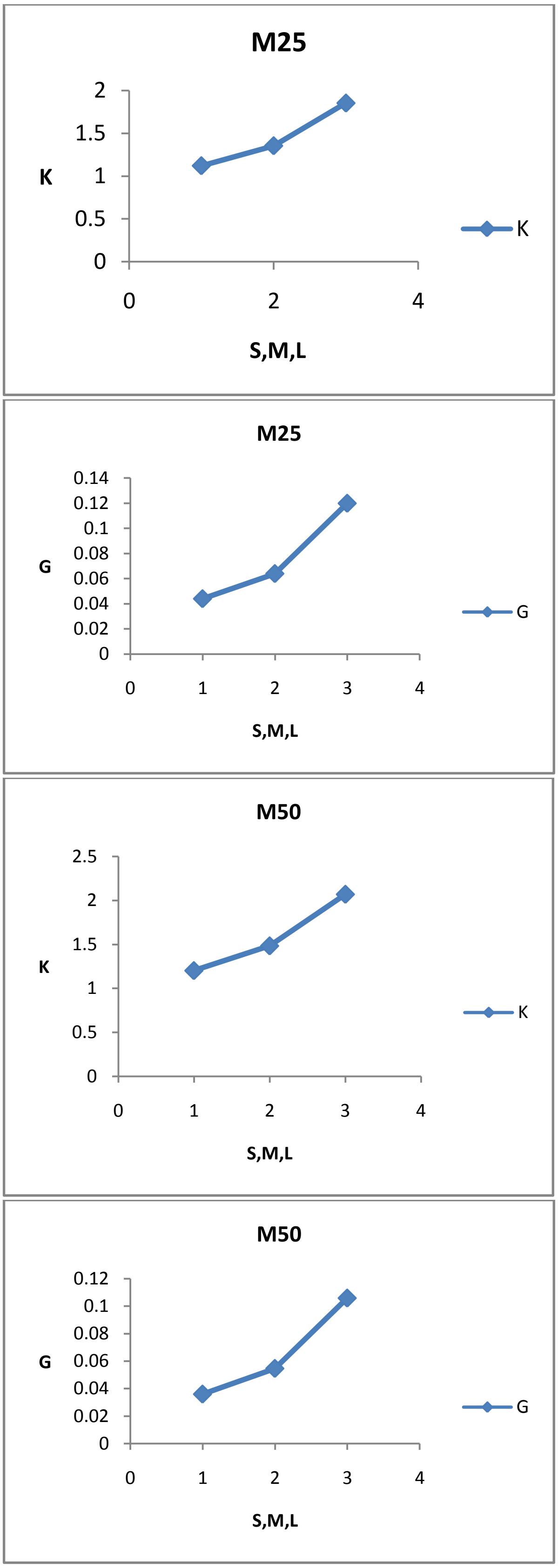
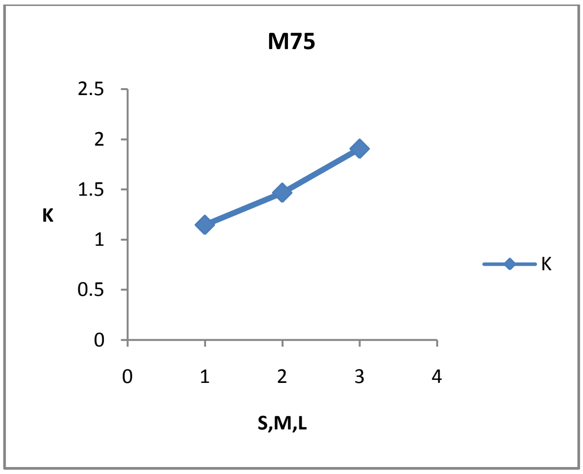


Fig 4.3: Graphs of Load vs failure stress and load vs shear stress for all grades of concrete



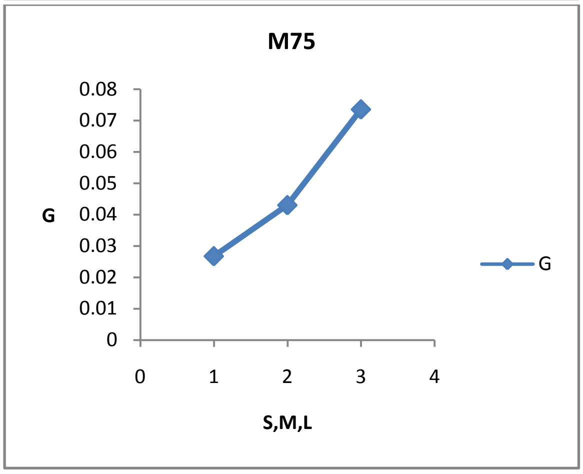


Fig 4.4: graphs of stress intensity factors vs beam sizes and fracture energy vs beam sizes for all grades

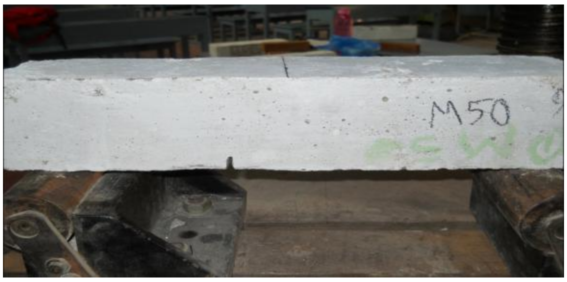


Fig.4.5: M50-Small beam before load

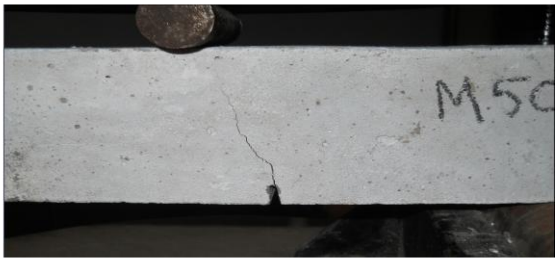


Fig.4.6: M50-Small beam after load

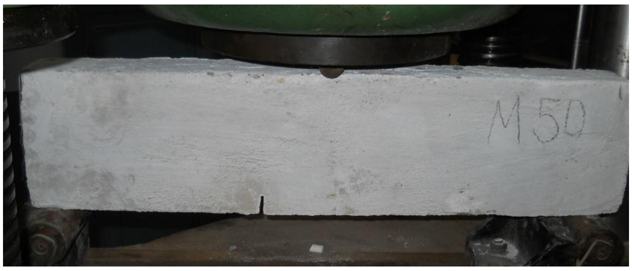


Fig.4.7: M50-medium beam before load

Fig.4.8: M50-medium beam after load

Fig.4.9: M75-small beam before load

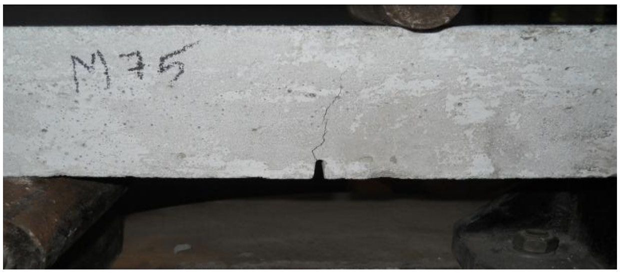


Fig.4.10: M75-small beam after load

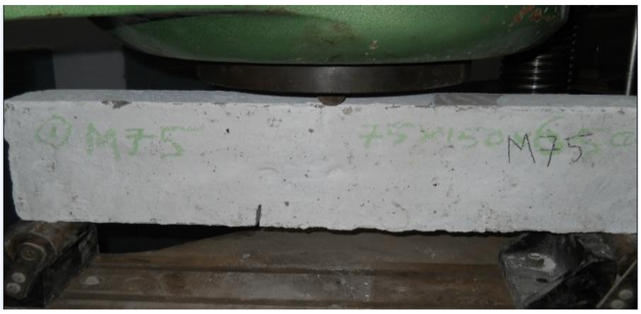


Fig.4.11: M75-medium beam before load

Fig.5.12: M75-medium beam after load

Fig: 4.13 & 4.14: M75-Large beam before Loading & after loading

Fig: 4.15: M25-Large beam before Loading & after loading

Fig: 4.16: M25-Large beam before Loading & after loading

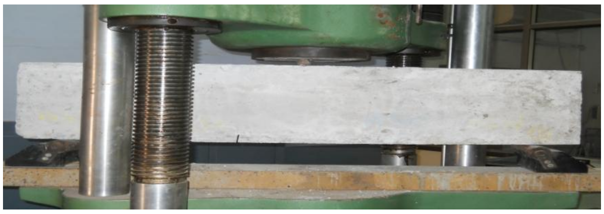


Fig: 4.17: M50-Large beam before Loading

Fig: 4.18: M50-Large beam after loading

5. ANALYTICAL WORK

5.0 ANSYS SOFTWARE:

ANSYS is a general purpose finite element modeling package for numerically solving a wide variety of mechanical problems. These problems include: static/dynamic structural analysis (both linear and non-linear), heat transfer and fluid problems, as well as acoustic and electromagnetic problems.

5.1 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.

6.1.1) Preprocessing
6.1.2) Solution
6.1.3) Post processing

5.1.1. **Preprocessing:-** Defining the problem involves the major steps like

- Define key points/lines/areas/volumes
- Define element type and material/geometric properties
- Mesh lines/areas/volumes as required
- Dimensionality of the analysis (i.e. 1D, 2D, axi-symmetric, 3D).

5.1.2. **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.

5.1.3. **Post processing: -** in this stage we can see

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

Table6.0: Comparison of failure stresses (normal and shear stress) from manual and ANSYS

sizes	UL kn	Experimental normal stress (n/mm^2)	Ansys normal stress(n/mm^2)	Ratio (σ_e/σ_A)	Experimental shear stress(n/mm^2)	Ansys normal stress(n/mm^2)	Ratio (τ_e/τ_A)
S-M25	6.000	7.445	6.615	1.125	0.667	0.540	1.235
M-M25	10.150	8.037	7.565	1.062	0.717	0.658	1.089
L-M25	16.500	7.660	8.511	0.900	0.683	0.637	1.072
S-M50	6.450	6.384	4.810	1.327	0.565	0.464	1.217
M-M50	11.150	7.009	5.284	1.326	0.620	0.510	1.215
L-M50	18.500	6.910	5.213	1.325	0.612	0.503	1.216
S-M75	6.150	6.181	7.464	0.828	0.416	0.500	0.832
M-M75	11.000	6.910	8.369	0.825	0.516	0.561	0.919
L-M75	17.000	6.360	7.691	0.826	0.475	0.515	0.922

U_L = ultimate load,

σ_e = Experimental normal stress,

σ_A = Ansys normal stress,

τ_e = Experimental shear stress

τ_A = Ansys normal stress

It is observed that the ratio between normal stress from experimental and Ansys varies from 0.900 to 1.125 for M25 grade concrete, 1.325 to 1.327 for M50 grade concrete and 0.825 to 0.828 for M75 grade concrete and also observed that the ratio between shear stress from experimental and Ansys varies from 1.072 to 1.235 for M25 grade concrete, 1.215 to 1.217 for M50 grade concrete and 0.832 to 0.922 for M75 grade concrete.

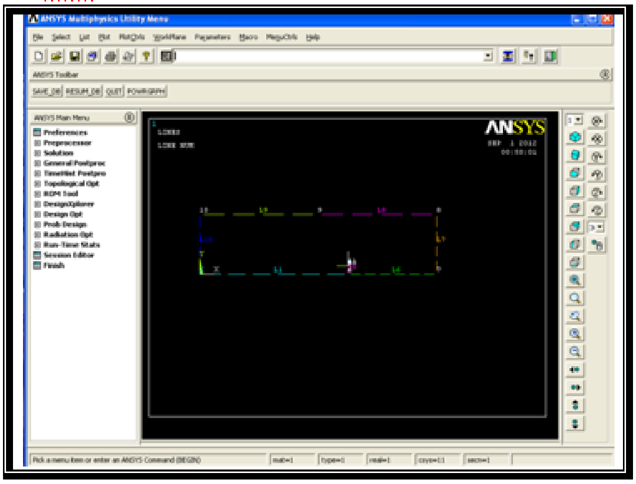


Fig.5.0: utility menu with beam in ansys

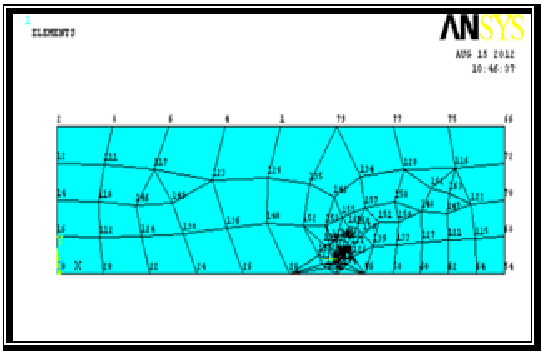


Fig. 5.1meashing the beam in to small elements in Ansys

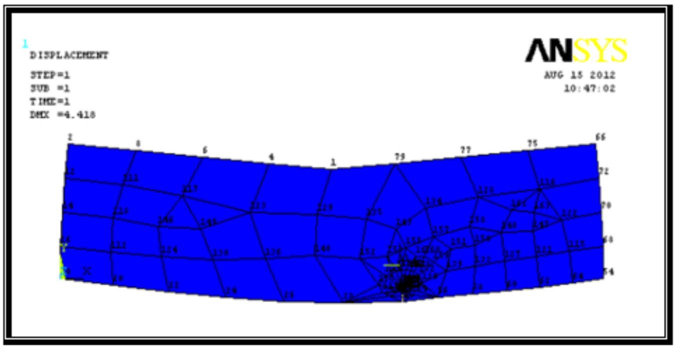


Fig.5.3: deformation of the beam in ansys

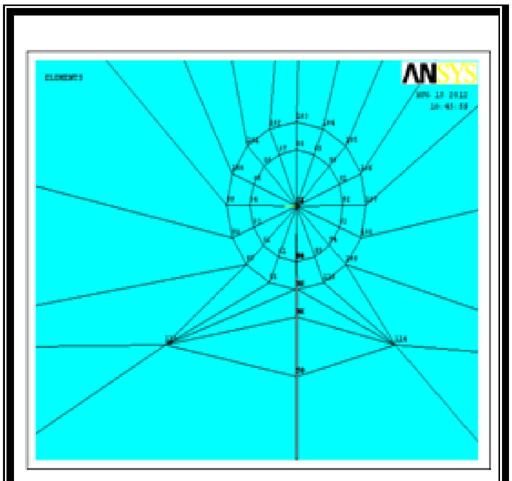


Fig.5.2: mesh at crack tip of the beam in ansys

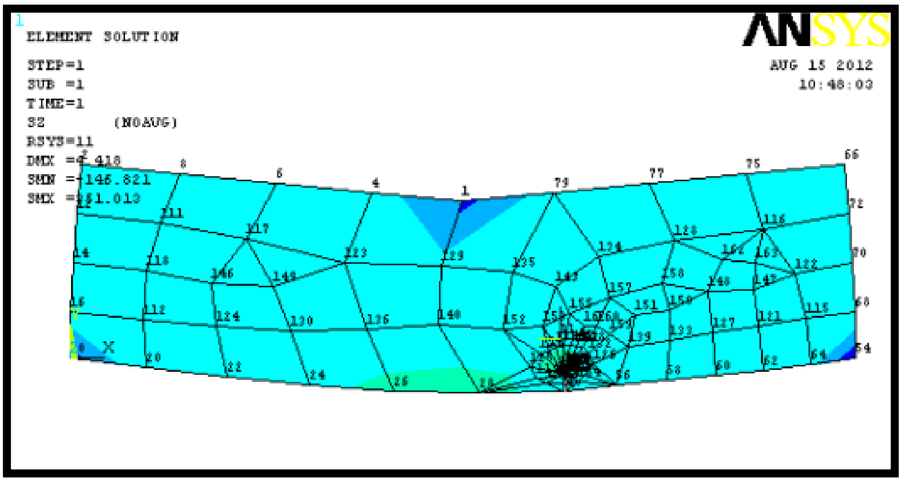


Fig.5.4: stress intensity in the beam in ansys

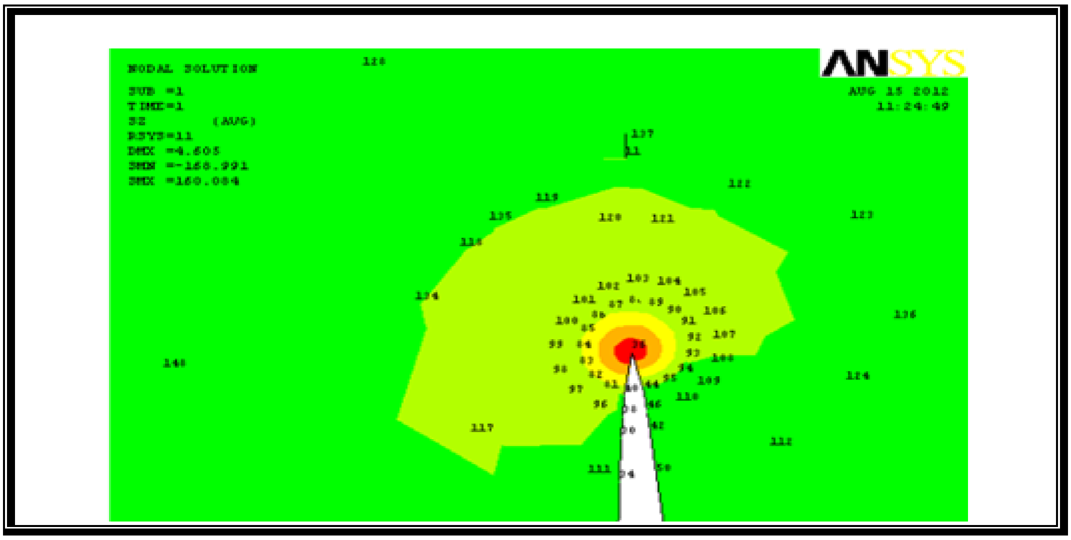


Fig.5.5: Stress intensity in the crack tip of the beam in Ansys

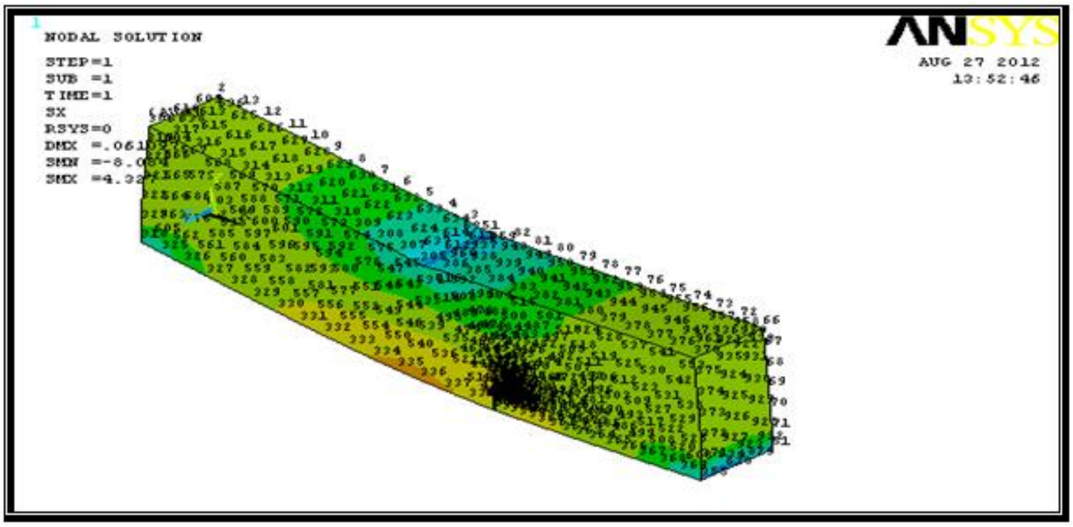


Fig.5.6: 3D of the beam showing failure stresses (normal) in ansys

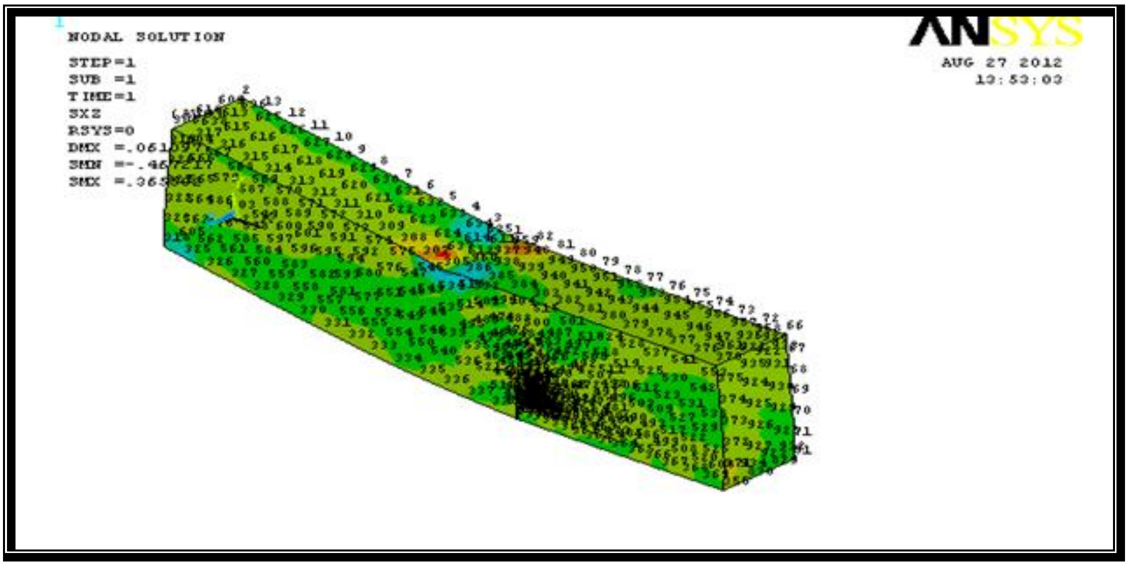


Fig.5.7: 3D of the beam showing failure stresses (shear) in ansys

CONCLUSIONS

Based on the tests on twenty seven notched concrete beam specimens, the following conclusions have been drawn:

1. It is observed that, failure stresses (normal stresses and shear stresses) decreases with increasing of beam sizes.
2. It is also observed that, stress intensity factor increases with increasing in beam sizes for all grades of concrete.
3. It is also observed that, fracture energy increases with increasing in beam sizes for all beams.
4. It is also notice that, the larger the beam, the more leaned towards the load point the crack trajectory was.

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