# FRACTURE MECHANICS IS THE SCIENCE OF STUDYING THE BEHAVIOUR OF PROGRESSIVE CRACK EXTENSION IN STRUCTURES SUBJECTED TO AN APPLIED LOAD

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**ABSTRACT**

*This is an experimental setup of casting plain concrete beams loaded till failure by providing a notch at the centre of the beam under the action of the load, to study the mode – 1 failure in fracture mechanics. Fracture mechanics is the science of studying the behaviour of progressive crack extension in structures subjected to an applied load.*

*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 size effects with three different mix proportions (M25, M50, and M75).*

*ANSYS is a general purpose finite element modelling 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. It is observed that, failure stresses (nominal stresses) decreases with increasing of beam sizes.*

***Keywords:ANSYS software, study the stress intensity factor and fracture energy of plain-high strength concrete beams.***

## I. INTRODUCTION

Fracture mechanics is the science of studying the behaviour 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.

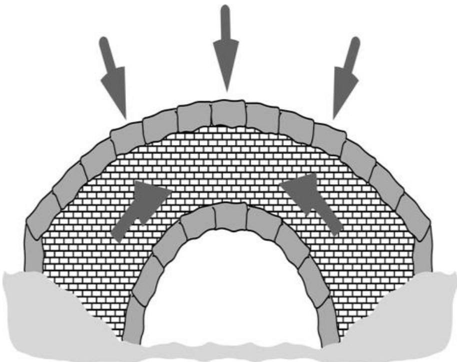
## 1.1 History Of Fracture Mechanics

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 durability of ancient structures is particularly amazing when one considers that the choice of building materials prior to the Industrial Revolution was rather limited. Metals could not be produced in sufficient quantity to be formed into load-bearing members for buildings and bridges.

Brick and mortar are relatively brittle and are unreliable for carrying tensile loads. Consequently, pre-Industrial Revolution structures were usually designed to be loaded in compression.



## 1.2 Fracture Mechanics

Fracture mechanics is the science of describing how a crack initiates and propagates under applied loads in many engineering materials like ceramics, rocks, glasses and concretes. Fracture mechanics is generally applied in the field of earth sciences such as petroleum engineering, geological engineering, mining engineering and civil engineering.

Materials like ceramics, rocks, glasses and concretes be have as brittle and in brittle materials; the crack initiation is determined by using the linear elastic stress field around the cracktip. This application belongs to Linear Elastic Fracture Mechanics (LEFM) assumption. This assumption is valid, when plastic deformation around the crack is negligible.

Concrete is a stone like material obtained by permitting a mixture of cement, sand and gravel or other aggregate and water, to harden in forms of the desired shape of the structure. Concrete has become a popular material in civil engineering for several reasons, such as the low cost of the aggregate, the accessibility of the needed materials and its high compressive strength.

### 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

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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.

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

$$\text{Л} = \text{Л}_e + \text{Л}_F + \text{Л}_K + \text{Л}_c$$

**Where,** $\text{Л}_e$= The elastic energy content in the body

$\text{Л}_F$ = The potential of the external forces

$\text{Л}_K$ = The total kinetic energy in the system.

$\text{Л}_c$=The fracture potential.

The fracture potential$\text{Л}_c$, is the energy that dissipates during crack growth. By assumingthat crack growth is only dependent on the crack length, a, the equilibrium equation canbe stated, by requiring that the potential energy of the system equals zero.

$$\partial \text{Л}/t^*\partial a = 0$$

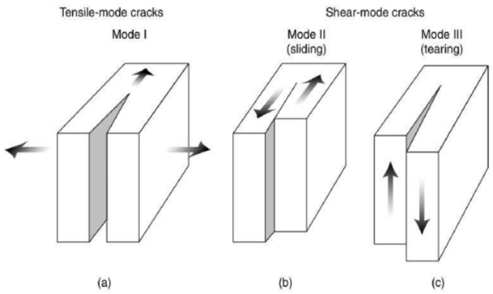
Griffith [1921] introduced a parameter, the energy release rate, **G**, and defined a fracture criteria.

$$G = -\partial \text{Л}_c/\ t^*\partial a = R$$

Where **R,** is the fracture resistance of the material, which is assumed to be constant in LEFM. The total potential energy of a system increases when a crack is formed because a new surface is created, thus increasing the fracture potential. However, the formation of a crack consumes an amount of energy, G in the form of surface energy and frictional energy. If the energy release rate is larger than the energy required for the formation of a crack.

$$\partial G/\partial a > \partial R/\partial a = 0$$

The method proposed by Griffith [1921] was based on energy considerations, but is not adequate in design situations. For this reason, Irwin [1958] developed the stress intensity factor, abbreviated SIF, concept. The SIF can be understood as a measure of the strength of a singularity, understood in the sense that the SIF amplifies the magnitude of the stresses around the singularity.




- Mode I fracture is the condition in which the crack plane is perpendicular to the direction of the applied load
- Mode II fracture is the condition in which the crack plane is parallel to the direction of the applied load.
- Mode III fracture corresponds to a tearing mode and is only relevant in three dimensions.

Mode I and mode II fracture is also referred to as an opening and in-plane shear mode, respectively. Irwin [1958] showed that the stress variation near a crack tip in a linear elastic material is dependent on the distance to the crack tip, called **γ**. More precisely, the stress is singular at the crack-tip with a square-root singularity in **γ**,

$\sigma_{ij} = K/\sqrt{2\pi\gamma}\ .f_{ij}(\theta)$ + higher order terms

**Where**

$\sigma_{ij}$= The stress tensor.

**K** = The stress intensity factor.

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$\theta,\gamma$= The polar coordinates at the crack-tip.

$f_{ij}$= A trigonometric function.

A linear relationship exists between the stress and the SIF, which reflects the linear nature of the theory of elasticity. In practical calculations, this is because, that for $\gamma\rightarrow0$, the first order term approaches infinity while the higher order terms are constant or zero. The stress tends towards infinity when $\gamma\rightarrow0$, a stress criterion as a failure criterion is not appropriate. For this reason, Irwin derived a relationship between the SIF and the energy release rate, ***G***,

$$K=\sqrt{G*E}$$

The fracture criterion can thereby be written as

$$K = K_c$$

**1.2.2loading Models**

Infracturemechanicsacrackcanbedefinedasaseparationinmaterial thatmay occurduetoslidingoropening. Suchseparationisoforder ofmicrostructures in material,likein homogeneities. The typeofloading conditions thatmake each ofthe typesofcrack are referred to asModeIforopening and ModeII andIIIforsliding.Inpracticalsituationsaloadingcondition withmixedmode happens whilepresence ofeachmodealoneismostlyreservedforexperimental cases.

**1.2.3 Process Region**

Regardless ofsizeofstructure,thewholefracture processtakes placeinasmall regionthatisnear crack edge,calledprocessregion. The sizeofprocessregioncomparedtodimensionofstructureorspecimen hasabigeffectonthefracture behaviour of thematerial.

**1.2.4 Energy Release Rate**

The crackpropagationleadstodissipationofstress strainenergy. This energy isdissipatedin processregionbecause offormationofmicro separationsand coalescences. Irwin was the first whoobserved thatifthe sizeofthe plastic zonearound crack tip issmall compared to the sizeofthe crack (i.e. brittle materials),theenergyrequiredtogrowthecrackwillnotbecritically dependent onthe state ofstress at the crack tip.

$$G = dU/da$$

Where,Uisthepotentialenergyavailableforcrackgrowth.

A is thecrackarea.

## 1.2.5 FRACTURE TOUGHNESS:

One of the underlying principles of fracture mechanics is that unstable fracture occurs when the stress intensity factor at the crack tip, K, reaches a critical value, Kc for Mode -1 deformation. The critical stress intensity factor for fracture instability is designated by $K_{Ic}$. $K_{Ic}$ represents the inherent ability of a material to withstand a given stress field intensity at the tip of n crack and to resist progressive tensile crack extension.Thus, $K_{Ic}$ represents the fracture toughness of a particular material, whereas $K_I$ represents the stress intensity ahead of a sharp crack in any materials.

## 1.2.6 SIZE EFFECTS:

Sizeeffectsinfracture mechanicscanberepresentedbythe concept ofnominal stressatfailure:

$$\sigma_n = C_N \frac{P_u}{bd} \quad \textbf{For 2-D problems}$$

$$\sigma_n = C_N \frac{P_u}{d^2} \quad \textbf{For 3-D problems}$$

Where$P_u$isthemaximumload, bisspecimen thickness,disthecharacteristic dimension ofthespecimen(e.g., itslengthor depth)and $C_N$isa parameter introducedforconvenience.

## 1.3 FRACTURE MECHANICS OF CONCRETE:

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Concrete is a heterogeneous anisotropic non-linear inelastic composite material, which is full of flaws that may initiate crack growth when the concrete is subjected to stress. Failure of concrete typically involves growth of large cracking zones and the formation of large cracks before the maximum load is reached.

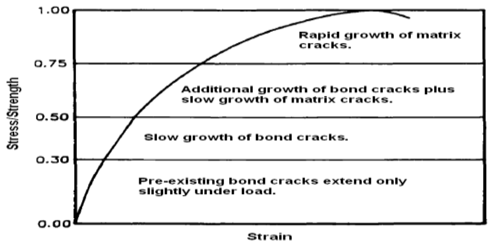
In 1983 Wittmann [1983] suggested to differentiate between three different levels of cracking in concrete. The levels are categorized as follows:-

- Micro cracks that can only be observed by an electron microscope.
- Meso cracks that can be observed using a conventional microscope.
- Macro cracks that visible to the naked eye.

Micro cracks occur on the level of the hydrated cement, where cracks form in the cement paste. Meso cracks form in the bond between aggregates and the cement paste. Finally, macro cracks form in the mortar between the aggregates.

### 1.3.1 THE FRACTURE PROCESS IN TENSION:

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.




### 1.3.2 THE FRACTURE PROCESS IN TENSION:

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.


*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.*

### OUTLINE OF EXPERIMENTAL PROGRAME:

This is experimental setup of casting plain concrete beams loaded to failure by providing a notch at the centre of the beam under the action of the load to study the mode – 1 failure in fracture mechanics.

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 size effects with three different mix proportions (M25, M50, and M75).

## MATERIALS FOR EXPERIMENT:

**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 X 75X75 mm
2. 600X 150X75 mm
3. 1200X 300X75 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.

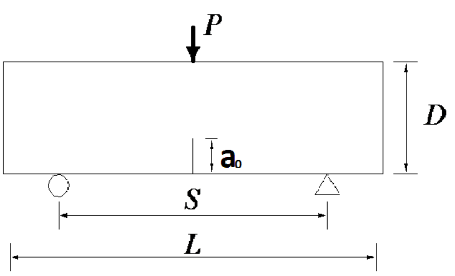
The prepared concrete was placed in the moulds and is compacted using needle& plate vibrators. The same process is adopted for all specimens. After specimens were compacted the top surface is levelled with a trowel.

**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.

## TEST SETUP AND TESTING PROCEDURE:

All the specimens were tested on the Servo controlled dynamic 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. 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. Dependent on the notch depth and the stiffness of the material andof the loading frame, the resultant load-displacement diagrams exhibitcatastrophic,semi-stable or stable fracture.




Where

P = LOAD APPLIED ON BEAM

D = DEPTH OF THE BEAM

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S = SPAN OF BEAM

L= TOTAL LENGTH OF BEAM

$a_0$ = CRACK WIDTH

**SIZE EFFECT LAW:**

According to Bazant and ZhipingOao, size effect in failure of concrete beams is given by the following formula.

$$\sigma_N = Bf_t\left(1+\frac{d}{d_0}\right)^{-\frac{1}{2}}$$

Where, $\sigma_N$ =Nominal stress

$f_t$ =direct tensile strength of concrete

B and $d_0$ are constants; d is the thickness of slab.

Nominal stress at failure due to flexure, may be expresses as

$$\sigma_n = C_N \frac{P_u}{bd}$$

In which $P_u$ is the maximum load at which failure occurred, b is the thickness of beam and d is the depth of the beam, Where $C_N$ is arbitrary constant for similar geometrical structures.

**RESULTS&DISCUSSIONS:**

For calculation of the stress intensity factor the following formulas are used

$$K_1 = \sigma_n\sqrt{\pi * a_0}\, f(\alpha)$$

$$\sigma_n = C_N \frac{P_u}{bd}$$

$a_0$ = Notch depth

$C_N$ = Arbitrary constant = 1.5(L/D)

$$f(\alpha) = \frac{1.99-\alpha(1-\alpha)(2.15-3.93\alpha+2.7\alpha^2}{(1+2\alpha)(1-\alpha)^{3/2}}$$ For beams having geometry of L/D = 4

$\alpha$ = Notch/Depth ratio = 0.15

$P_u$=failure load

b = thickness of the beam

d = depth of the beam

After finding the value of stress intensity factor $K_1$ value then the value of the fracture energy is obtained in non-linear fracture approach by the formula

$$G_f = \frac{g(\alpha)}{EA}$$

$$g(\alpha) = C_N^2\pi\alpha f(\alpha)^2$$

E = young's modulus of concrete = 5700√fck

A = constant obtained from regression plot

After obtaining the value of fracture energy $G_f$the brittleness number is obtained by formula

$$\beta = \frac{d}{d_0}$$

d = depth of beam, $d_0$ = C/A taken from regression plot

The formula for cohesive fracture zone length is

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$$Cf = \frac{g(\alpha)}{g'(\alpha_0)} d_0$$ where, **g'(α)** = derivative of g(α) with respect to α

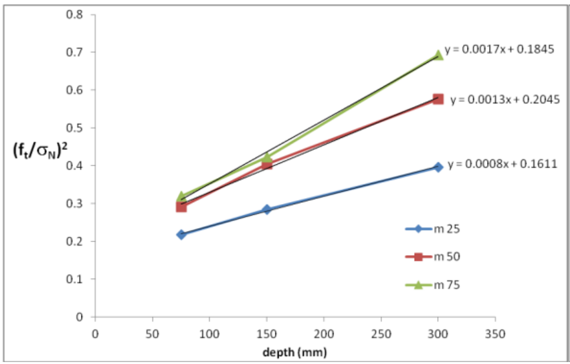
**Failure loads, Nominal stresses, Stress Intensity Factors:**

| Concrete grades | Specimen | $p_{max}$ KN | $\sigma_N$ (N/mm$^2$) | $K_I$ (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 |

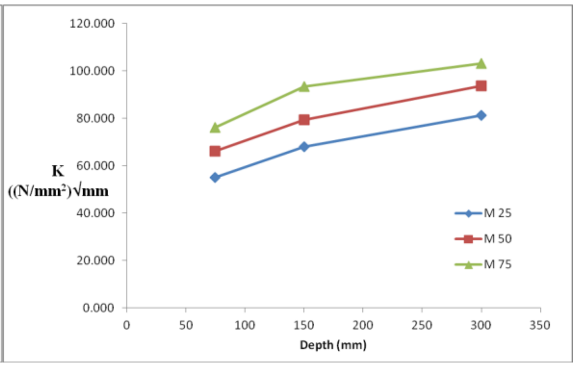
**Fracture Energy, Brittleness number, Cohesive Fracture Zone length:**

| Concrete grades | Specimen | $G_f$ j/m$^2$ | β | $C_f$ Mm |
|---|---|---|---|---|
| **M25** | 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 |

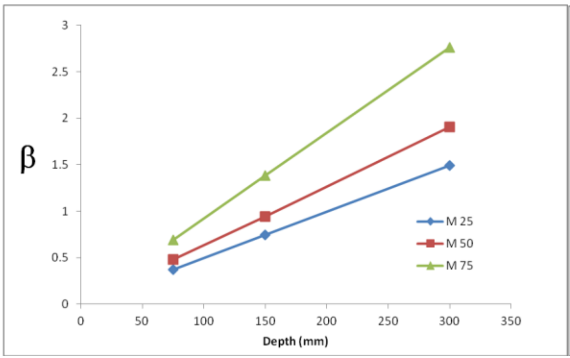
## GRAPHICAL REPRESENTAION OF VALUES OBTAINED FROM EXPERIMENT:



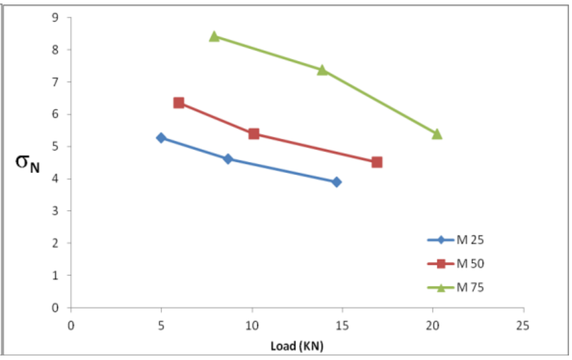

*Regression graphs*



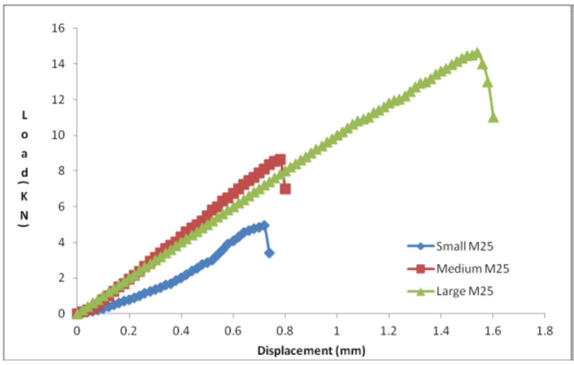

*Stress Intensity Factor curves for Depth of beams*



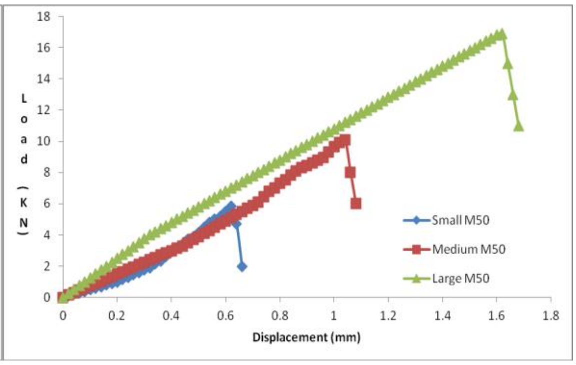

*Brittleness number curves for Depth of beams*



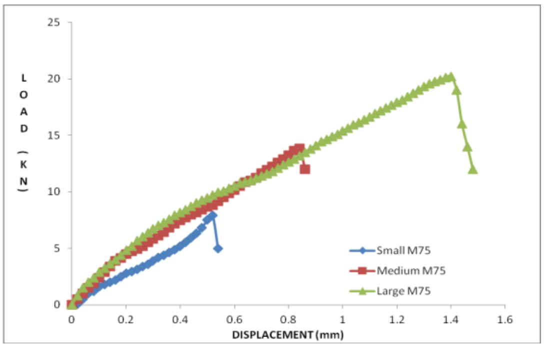

*Nominal Stresses Vs Load graph*




*Load Vs Displacement graph for M 25 grade beams*




*Load Vs Displacement graph for M 50 grade beams*




*Load Vs Displacement graph for M 75 grade beams*

## ANALYSIS OF VALUES OBTAINED FROM EXPERIMENT USING ANSYS:

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**BRIEF INTRODUCTION:**

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.


Snapshot of ANSYS work screen

### 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) **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).

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.

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

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

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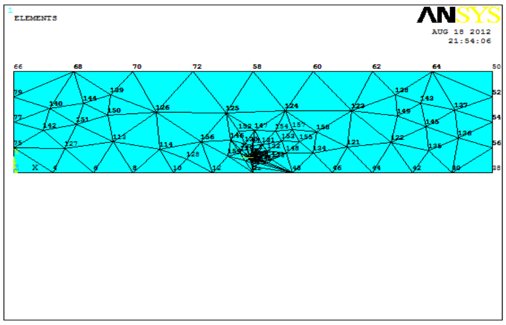
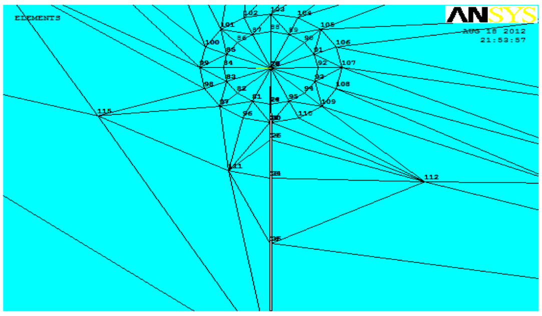
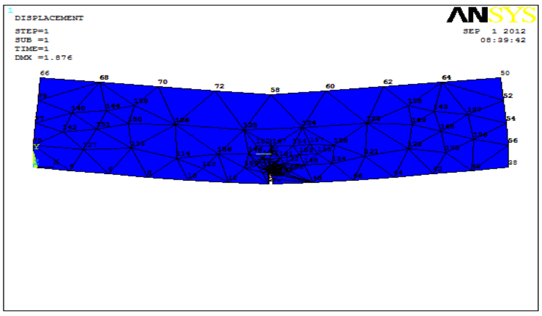
utility menu with beam in ANSYS



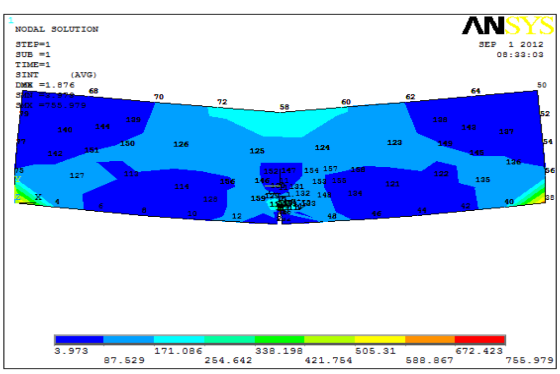
meshing the beam in to small elements in ANSYS



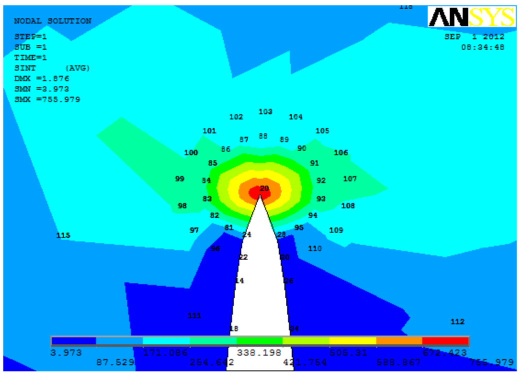
mesh at crack tip of the beam in ANSYS



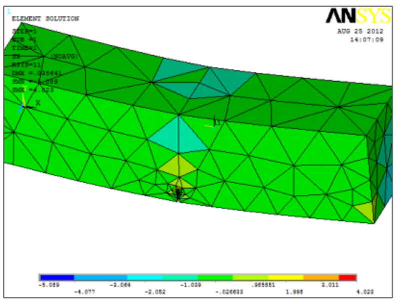
deformation of the beam in ANSYS



stress intensity in the beam in ANSYS



stress intensity in the crack tip of the beam in ANSYS



3D of the beam showing failure stresses in ANSYS

### III. CONCLUSION

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

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

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