Determination of Fracture Parameters of Conventional Concrete Using ANSYS

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Abstract - *It is found that strength of concrete structures generally decreases with increasing structure size before reaching a limiting value. This effect must be taken into account in the design of the ultimate behavior of concrete structures in order to avoid damage and crack openings. Fracture mechanics is used to predict such size effect. Stress intensity factor (SIF) is the base parameter in strength analysis regarding fracture mechanics. Hence study of fracture parameters will help to prevent catastrophic failures of structures and will be one of the important aids in material engineering. In order to investigate the fracture behavior the concrete beams of 1200mm×100mm×200mm with 2mm wide notch and 0.15 notch depth ratio. The concrete beam is modeled using 'CONCRETE65'- which is capable of simulating the cracking and crushing behavior of brittle materials. The study is carried out on beams of grade M30. Fracture parameter considered here is a Stress Intensity Factor (K), Fracture energy (G) and energy release rate. The analytical result obtained by developing finite element model of the beams using ANSYS 17.1 of conventional concrete. These parameters would help in designing of safe structures where micro cracks are given the at most importance.*

Key Words: **Ansys 17.1, Finite element method, Concrete specimen, Stress intensity factor, Fracture energy, Energy release rate.**

1. INTRODUCTION

Safety is an essential concept of engineering design and it tends to receive greater attention when the consequences of failure are severe. The concept of designing solely for strength and using highest strength material without regard to fracture toughness is unreliable. The conventional stress-based approaches assume the component is homogeneous and do not have flaws present in them. But unfortunately in reality all the structural components have some defects or flaws in them. If these flaws are not considered, the structural component may fail well before its ultimate strength. Hence the structure must be designed considering the defects or flaws in structural components.

Cracks in concrete structures can indicate major structural problems and detract from the appearance of monolithic constructions. Cracking plays an important role in concrete's response to load in tension and compression. The earliest studies of the microscopic behaviour of concrete involved the response of concrete to compressive stress. The early work shows that the stress-strain response of concrete is close with the formation of micro cracks at coarse-aggregate boundaries and propagates through the surrounding mortar.

Fracture mechanics has as primer objective predicts if a structure will fail or not by the presence of a crack. Stress intensity factor KI is quantified by performing crack analysis starting from field stresses in the crack tip,. Thus, comparing KI value with a peculiar characteristic of each material, called fracture toughness, it´s possible to predict if a crack member will fail or not when submitted by severe loads. It´s well common a crack happen due to an unexpected over-loading in a structure no damaged. Usually this happens by a fail or a crack in the structure submitted by a cyclic loading or a normal service loading. In this way, the crack can growth starting from a fail or any stress concentration, decreasing the structure mechanical resistance until it´s collapse. With large using of mechanical components under fatigue conditions, fracture mechanics is no longer just a problem of design engineers, who concerns about mechanical components life. Fracture mechanics is a powerful tool for advanced study, which is widely achieved by any engineering student nowadays. Thus, this work presents a educational approach, showing some computational fracture mechanics tools as ANSYS.

Fracture mechanics provides just such a general failure theory. The linear elastic fracture mechanics LEFM has been available since 1920 (Griffith 1920, 1924). But, its absence from the codes of practice for the design of concrete structures is not because of oversight or ignorance on the part of Code committees. Rather it is because the Griffith fracture theory is only applicable, to elastic, homogeneous brittle materials, such as glass. The usefulness of the theory of fracture mechanics in the design of plain and reinforced concrete structures emphasizing the effect of structural size on the failure load and mode. We noted that small structures appeared to fail in a ductile manner whereas large structures exhibited a brittle mode of failure. In fact for very small structures the current plastic limit analysis is quite adequate, whereas the classical linear elastic fracture mechanics (Griffith theory) is applicable without any modifications to large concrete structures containing negligible amount of reinforcements such as gravity dams plinths of bridge piers etc.,

1.1 History

1.1.1 Application of Fracture Mechanics to Concrete

Since Kaplan first measured the fracture toughness and strain energy release rate of concrete in the early 1960s [Kaplan 1961], much theoretical and experimental work has been done to assess whether linear elastic fracture mechanics (LEFM) could be directly applied to concrete materials. Concrete is neither a perfect elastic brittle material like glass nor a quasi-brittle material and shows some non-linearity before the peak load is reached. Accordingly the stable crack growth, also termed as the fracture process zone, occurs due to micro cracks in the mortar and bond cracks at the cement paste-aggregate interface, or crack arresting, kinking and linking between aggregate particles, or a macro crack. All of this makes the measured fracture toughness become geometrically dependent. To accurately determine the fracture toughness of concrete, the stable crack growth has to be added to the initial notch depth and the effective crack length is adopted. The geometrically true material properties as fracture toughness were obatined independently. Hillerborg used the fictitious crack model to determine fracture energy [Hillerborg et al 1976]. Bažant et al used the size effect model and the crack band model to determine *R*-curve parameters, fracture energy, crack band width, strain softening modulus, etc. Karihaloo and Nallathambi has proposed the effective crack model based on the massive test data for calculating the fracture toughness.The effects of crack size , ratio of water/cement and coarse aggregate texture on the fracture toughness of concrete etc were investigated, also the empirical formulae is very convenient to use .Shah proposed the two-parameter fracture model so as to eliminate the effect of geometry to work out the effective crack length [Shah 1990]. RILEM [RILEM 1990a, 1990b] proposed the drafts for determining the fracture toughness K_{IC} and the critical crack tip opening displacement $CTOD_C$ by using either Shah's two-parameter model [Shah 1990] or Bažant's size effect model [Bažant et al 1986]. Guinea, Planas and Elices [Guinea et al 1992; Planas et al 1992; Elices et al 1992] identified possible sources of the experimental error in the RILEM method [RILEM 1985] for measuring the fracture energy and proposed a method to eliminate the major source of the error by including the work-of-fracture due to practical difficulties in capturing the tail part on the load-deflection curve. Their model was later applied and developed further [Rosselló and Elices 2004; Rosselló et al 2005]. Direct tension test [Phillips and Zhang 1993] and splitting tension test [Ince 2010] were done to obtain stable fracture toughness of concrete Xu and Reinhardt proposed the double-*K* fracture model to simulate the fracture of concrete including the initial fracture toughness *K* unstable fracture toughness K_{IC} [Xu and Reinhardt 1999a, 1999b, 1999c, 2000]. These two fracture toughness parameters were obtained from the initial fracture energy release rate G_{iniIC} and the unstable fracture energy release rate G_{unIC} measured on compact tension, wedge splitting and three-point bending concrete specimens. Zhao , Kwon and Shah used inverse analysis on the test data , to investigate the effect of specimen size ,on the fracture energy and the softening curve of concrete [Zhao et al 2008 ; Kwon et al 2008] Very recently, Murthy and Karihaloo extensively investigated the size effect on the specific fracture energy of normal and high strength concrete using trilinear and other methods [Karihaloo et al 2013; Murphy et al 2013].

2. REVIEW OF LITERATURE

2.1 Summary

The need and scope of present investigation is,

Despite their apparent overdesign, the metal structures and components did not always function satisfactory and experienced occasional unexpected failures.

If the crack grows long enough, sudden failure can occur with catastrophic consequences. In concrete, flaws are not avoidable but the knowledge on critical size of crack is mandatory in order to prevent sudden failure. 'Prevention is better than cure' so before the crack propagate and leads to severe life and economical damage we must have control over it. The micro structural study of concrete is needed to avoid macro level damages. By foreseeing in a future scope the crack study of the concrete is needed to avoid many structural collapses.

Fracture parameters are stress intensity factor, fracture energy, energy release rate determined to predict the failure of material. The material is going to fracture due to high tensile stress, rapid rate of loading and presences of notches. The reason behind the fracture parameters is to avoid the failure of concrete. The critical load is the limiting load when the fracture parameter reaches the critical value. Under certain circumstances the load exceeding critical load of the material, the crack start to propagate.

The objective of the present investigation is,

- To calculate the fracture parameter critical stress intensity factors for the concrete grade M30 subjected to the condition that notch to depth ratio is 0.15.

- Fracture parameters calculated are Stress Intensity Factor (K), Fracture Energy (Gf), Energy Release Rate (G).

3. METHODOLOGY

3.1 Analytical approach

3.1.1 Fracture Toughness of Concrete

In the linear fracture mechanics (LEFM), the fracture toughness for mode I, K_{IC}, also called the critical stress intensity factor, is general calculated from,

$$K_{IC} = \sigma_N \sqrt{a}\, F(\alpha) \qquad (1)$$

where,
σ_N is the nominal applied stress,
a is the effective crack length, $a = a_0 + \Delta a$,
a_0 is the initial notch depth,
Δa is the crack propagation at peak load and is also widely regarded as the size of the process zone or crack zone,
α is the effective notch-depth ratio and $\alpha = a/H$,
H is the specimen depth,
$F(\alpha)$ is a geometric function.

Thus Eq.(1) is used to determine K_{IC} and σ_N in Eq.(1) is equal to the modulus of rupture of the corresponding un-notched beam and can be expressed by considering the self-weight of the beam as

$$\sigma_N = \frac{6\,M}{B\,H^2} = \frac{1.5(P_U + P_O)S}{BH^2}$$

$$\sigma_N = \frac{1.5\left[P_U + 0.5\,m\,g\left(\frac{L}{S}\right)\left(2 - \left(\frac{L}{S}\right)\right)\right]S}{BH^2} \qquad (2)$$

Where,
B is the width of the beam,
L is the full length of the beam,
S is the effective span,
M is the maximum moment at the middle span, given by $M = (P_u + P_0)\,S/4$,
P_u is the maximum load at peak,
P_0 is the equivalent load due to the self-weight of the beam and
$P_0 = 0.5mg\,(L/S)(2-L/S)$,
m is the mass of the beam between the supports and is calculated as $m = m_0(S/L)$,
m_0 is the total mass of the beam,

g is the acceleration due to gravity and $g = 9.81\ m/s^2$.
Here, the factor (L/S) (2-L/S) is used to eliminate the influence of the cantilever parts of the concrete beam outside the supports

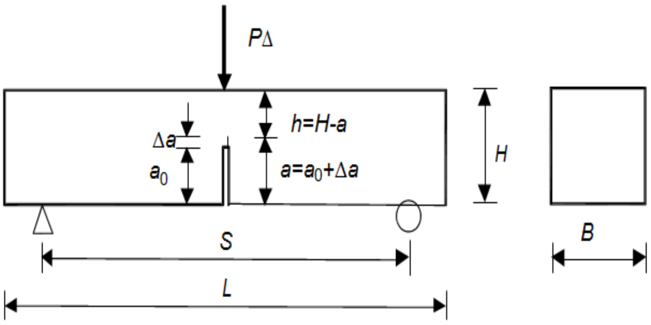


Fig -1: Dimensions of a single edge notched beam

Here the ligament height h is equal to $H-a$. At high temperatures, the self weight of the beam will no longer be constant but very much depend on the heating scenario. Hence m should be replaced by the actual mass m' which is defined

$$m' = m\,(1-\omega) \qquad (3)$$

Where ω is the percentage weight loss during heating, greatly dependent on heating scenarios. For $S/H = 4.8$, the geometric function $F(\alpha)$ can be expressed as [Karihaloo and Nallathambi 1989; RILEM1990a]

$F(\alpha) =$

$$\frac{1.99 - \alpha(1-\alpha)(2.15 - 3.93\,\alpha + 2.70\,\alpha^2)}{(1+2\,\alpha)(1-\alpha)^{3/2}} \qquad (4)$$

In the process for determining K_{IC}, σ_N is first calculate using Eq.(2), then followed by determining $F(\alpha)$ using Eq.(4), and finally calculating K_{IC} using Eq.(1).

3.2 Fracture energy

The great break strength KIC is gotten in light of a definitive load, including straight stacking and solidifying. It can be used to reflect the resistance of concrete against cracking. However, it cannot represent the crack resistance of the heated concrete. In other words, the crack resistance of concrete can be represented using load capacity and deformation ability, i.e. energy dissipation. This resistance can be well reflected using the fracture energy G_f.

$$G_f = \frac{w}{A_S} \qquad (5)$$

where,

W= P x deflection

A_S= Area of fracture = a x d a
is the effective crack length

3.3 Energy release rate

The more energy is released for unit increase in area during crack growth is given by

$$K_{IC} = \sqrt{GE} \qquad (6)$$

Where,
K_{IC} =Critical Stress Intensity Factor,
G = Energy release rate,
E = Young's modulus of concrete
$E = 5000\sqrt{f_{ck}}\,/\,(1-\nu^2)$ for plane strain condition,
where, ν= Poisson's ratio

Thus, the fracture toughness related to fracture energy, K_{IC}, can play this important role. Because K_{IC} can represent the behavior of concrete at both ascending and descending branches of the complete loading process including linear, hardening and softening, its magnitude can be expected to be larger.

4. COMPUTATIONAL APPOROACH

4.1 Modelling the crack region

The concrete beam having original dimension of 1200mm×100mm×200mm was modeled in ANSYS 17.1. The most important region in a fracture model is the region around the edge of the crack. The recommended element type is node CONCRETE 65 elements. The model was meshed as tetragonal mapped elements. The support conditions provided are simply supported with an effective span of 960mm. This model was analysed as static, linear, elastic, homogeneous material with modulus of elasticity of 28527 N/mm² for conventional concrete and poisons ratio = 0.2.

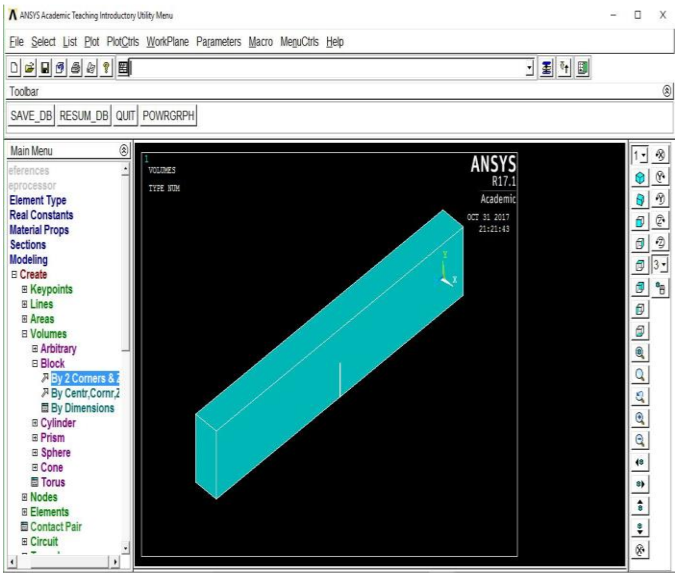


Fig -2: Beam model

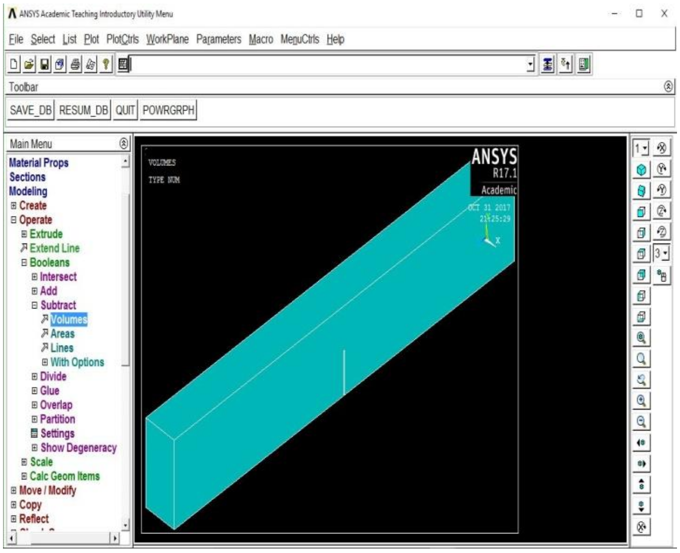


Fig -3: Beam model with pre-crack

Utilizing volume clearing, you can fill a current unmeshed volume with components by clearing the work from a bouncing region (called the "source territory") all through the volume. If the source area mesh consists of quadrilateral elements, the volume is filled with hexahedral elements. If the area consists of triangles, the volume is filled with wedges. In the event that the territory comprises of a blend of quadrilateral and triangular components, the volume is loaded with a mix of hexahedral and wedge components. The swept mesh is fully associated with the volume.

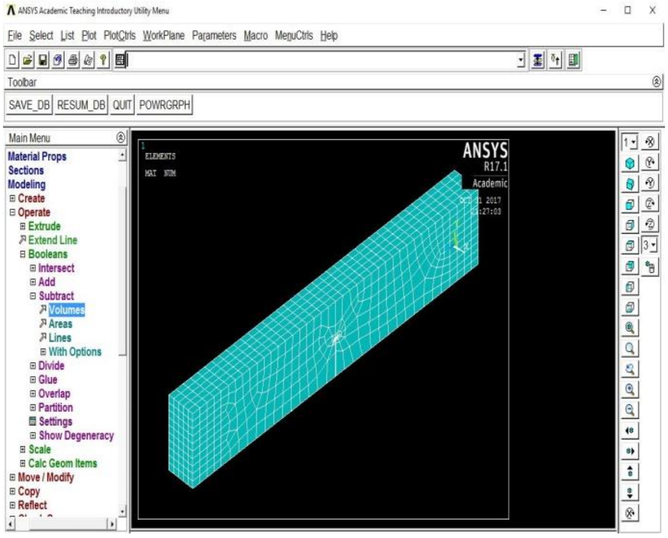
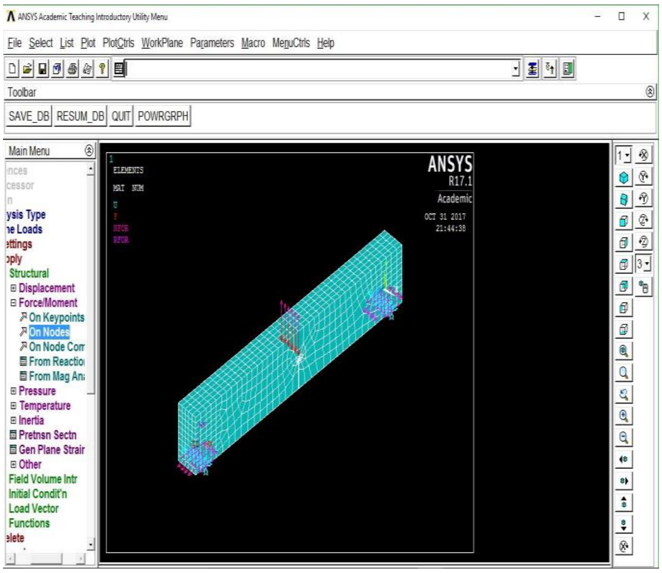


Fig -4: Meshed Beam model

Most loads either on the solid model or on the finite element model. For instance, you can determine powers at a key point or a hub. Thus, you can determine convections on lines and territories or on hubs and component faces. No matter how you specify the loads, the solver expects all loads to be in terms of the finite element model.



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ELEMENTS
MAT NUM
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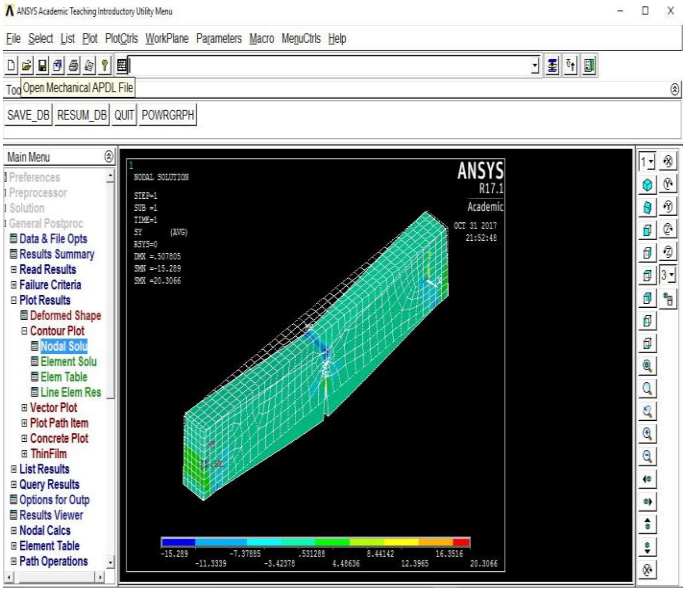
Fig -5: Beam model with loads and supports

5. Results and discussion

5.1 Stress patterns

SIZE OF THE SPECIMEN: 1200mm×100mm×200mm



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NODAL SOLUTION
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TIME=1
SY       (AVG)
RSYS=0
DMX =.507805
SMN =-15.289
SMX =20.3066
OCT 31 2017
21:52:48
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Fig -6: Y-component stress of conventional concrete specimen

The Fig -6 shows the Y-component stress patterns of the conventional concrete specimen.

5.2 Effective Crack Length

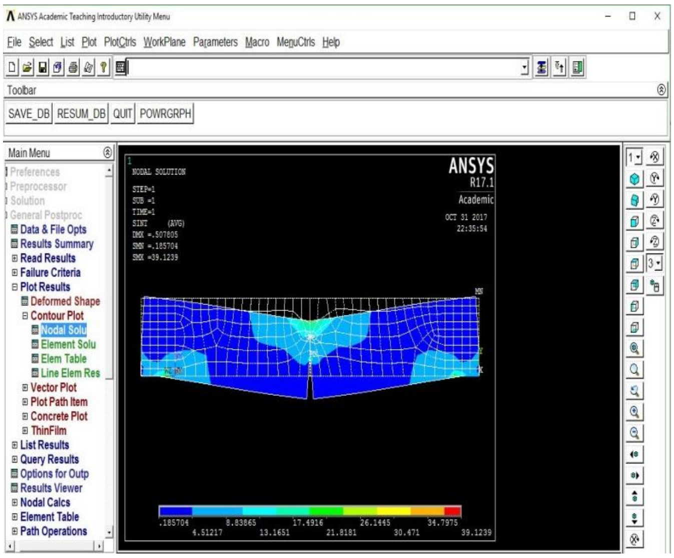
a is the effective crack length,

$a = a_0 + \Delta a$,

a_0 is the initial notch depth,

Δa is the crack propagation at peak load and is also widely regarded as the size of the process zone or crack zone.

5.3 Crack length and deflection



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NODAL SOLUTION
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SUB =1
TIME=1
SINT     (AVG)
DMX =.507805
SMN =.185704
SMX =39.1239
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22:35:54
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Fig -7: Fracture process zone length and maximum deflection of beam model

From the Fig -7 the size of the process zone or crack zone is found to be 30mm and maximum centre point deflection was found to be 0.507mm.

a= 0.060 m

5.4 Fracture parameters

- From the computational study of stress intensity of M30 grade of conventional concrete specimen was found using ANSYS 17.1. Stress intensity factor the critical stress intensity factor was found to be **1.08370 MPa$\sqrt{m}$.**

- The value of deflection of finite element model is found to be **0.507 mm**, which is used to find the fracture energy. The fracture energy was found to be **0.2916 N / mm^2.**

- The energy release rate for conventional concrete is found to be **0.04289 N/mm.**

6. SUMMARY AND CONCLUSION

In conclusion of the present work, it may be emphasized that fracture mechanics offer a realistic and consistent approach to the analysis of cracking in concrete structures. From the investigations, various fracture parameters such as critical stress intensity factor, fracture energy and energy release rate of conventional concrete evaluated.

K_{IC} is an instantaneous parameter and represents the cracking resistance at the peak load and it is a more synthetic process parameter and represents the resistance over the whole fracture process.

6.1 CONCLUSION

- Stress intensity factor depends on critical load which in turn depends on the notch depth of specimen and is found to be reducing on increasing the notch depth
- Since critical stress intensity factor (K_{IC}) is the material property, for any structure subjected to a crack with particular notch to depth ratio, critical stress intensity factor (K_{IC}) for the respective value notch to depth ratio could be used.
- By knowing the critical stress intensity factor for the particular notch to depth ratio, the critical stress (σ_N) at which the failure occurs can be predicted for any structure subjected to crack.
- By increase in load, the crack propagation occurs. The critical crack length (a_c) at failure stage can be predicted from the known values of critical stress intensity factor (K_{IC}) and critical stress (σ_N) and thus we could prevent the structure from sudden catastrophic failures.
- Critical Stress Intensity (K_{IC}) factor obtained here could be applicable only for brittle structures and for structures having negligible plastic zone size.

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