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ASSESSMENT OF FATIGUE CRACK GROWTH ON COMPACT TENSILE MILD STEEL SPECIMEN UNDER SUDDEN LOAD

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ABSTRACT

To evaluate the residual fatigue life of components, the fatigue life prediction based on crack growth analysis has been presented, although it requires the specification of an initial fault. If there are always early imperfections on materials, serving as comparable starting cracks, Fracture Mechanics crack growth-based fatigue predictions may be utilized as an alternative to simulate the entire fatigue life of structural components. Very few researchers have addressed the issue of enhance fatigue life due to impact load also very less investigation has happened on effective and efficient assessment of Stress Intensity Factor (SIF) through numerical approach. This research mainly focuses on extracting Stress Intensity Factor for In-plane Mode I loading and efficient utilization of local coordinate system displacement to extract accurate Stress Intensity Factor (SIF) computational. Taking different (a/W) values to predict the critical crack length & extract stress intensity factor through computational and analytical & validated through experimental.

Keywords: Stress Intensity Factor, Fatigue Crack Growth, Damage Tolerant Design.

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INTRODUCTION

Fracture has been an issue in civilization for as long as there have been man made buildings because of this, the situation may be greater today than in prior ages. Major airline disasters would not be feasible in the absence of contemporary aeronautical technology. Fortunately developments in fracture mechanics have helped to mitigate some of the risks posed by rising technological complexity. Since World War II our understanding of how materials fails and our capacity to prevent such failures has grown significantly [1-2].

The capacity to tolerate a significant amount of damage is a need for modern structures, hence it has become more vital to improve approaches to predict failure in fatigue damaged components. Damage tolerance assessments may be performed using linear elastic fracture mechanics (LEFM) ideas which include T-stress, higher order terms ,and the stress intensity factor (SIF) which plays a significant role [2-5]. The fracture Mechanics theory is widely used in conjunction with crack development rules such as Paris law to assess and predict crack growth and fracture behaviour of structural components. In components and structure subjected to cyclic load, fatigue resistance is critical. The damage tolerance strategy entails designing structural components with a specific allowance for minor fractures , the existence of which must be monitored on a regular basis . It is especially suggested for sectors where flaws are unavoidable such as welding , casting or additive manufacturing . One of the most important components of the damage tolerance technique is the ability to correctly calculate and anticipate the rate of fatigue crack growth. While catastrophic failures provides revenue for attorneys and consulting engineers. This study projected that if current technology were used , the yearly cost could be cut by $35 billion and that further fracture mechanics research might decrease this figure by a further $28 billion. [6-10].

One of the most common causes of failure in engineering constructions is fracture, especially in brittle materials where it can happen suddenly and without any warning. When a structure has a stress raiser factor like a fracture or notch, the issue gets worse. To forecast the fracture load in engineering structures with discontinuities like cracks or notches, many criteria have been presented by researchers. The temperature of the materials is affected by heat dissipation and plastic deformation, which are closely connected to fracture damage.

Instead of processing the temperature field as in thermo-graphic measurements, sophisticated infrared cameras have been employed to process the local fluctuating temperature components and, consequently, the thermo-elastic effect. TSA often doesn't require any extra sample preparation, therefore the measuring approach doesn't need a lot of setup time. [7-11]

The experimental examination of stresses or displacements around the expanding fatigue fracture's tip is important in the research of crack propagation. Different fatigue and failure processes are now well understood because to modern experimental techniques like displacement image correlation (DIC) and thermo-elastic stress analysis (TSA). In this regard, TSA appears to be an incredibly ideal method for researching crack shielding. The approach measures minute temperature changes at the surface of the structure resulting from cyclic loading and produces comprehensive field stress maps from the surface of structural components. [8-14]

FATIGUE CRACK GROWTH

Engineered parts frequently develop cracks, which greatly lowers their capacity to bear strain. Cracks frequently develop around preexisting imperfections in a component. Typically, they begin modest and subsequently expand as they are used. A fracture will develop in a component when there is cyclic applied stress or when there is a constant load in an unfriendly chemical environment. This article focuses on fatigue crack growth, which is the crack growth brought on by cyclic loading. Environmental crack growth, which is not covered here, is the process of crack growth in an unfavourable environment. The fracture mechanics ideas covered on this page are crucial for the investigation of fatigue crack development. [1-4].

A process known as fatigue fracture development happens in materials that are subjected to cyclic loading. It describes the progressive spread of cracks within a material when loading and unloading circumstances are repeated or cyclical. This phenomena is crucial to engineering and materials science, particularly for the design and upkeep of components and structures that are susceptible to varying stresses. Cracks can start and spread over time when a material is subjected to cyclic pressure, such as the alternating tension felt by aircraft wings during takeoff and landing or the recurrent loading on a mechanical component. These cracks typically start at places of high stress, flaws, or stress concentration spots within the material. [6-10]

The fracture of materials has been studied for a long time. Griffith proposed a fracture criteria based on energy release rate Subsequently Irwin introduce the concepts of stress intensity factor which established the relationship with release rate based on crack tip opening displacement theory proposed by Wells . As a gauge of a material's resistance to crack extension, fracture toughness, play a crucial role in the criteria available for predicting the load bearing capacity of cracked or notched structures. The critical stress intensity factor describes the state of stress around an unstable crack or flaw in a material and is an indication of stress required to produce catastrophic propagation of the crack .Stress Intensity Factor are well known parameters which explain the characteristics of a crack [1-5].

Edmundo R. Sergio .et.al studied the combination of Gurson Trergaard Needleman damage model with a numerical model that employs the cyclic plastic strain at the crack tip to estimate da/dN. It is concluded that at low levels of K, plastic strain caused an unexpected reduction in da/dN [1]. J H Kuang et.al extrapolated the stress intensity factors of modes I and II from the relative opening and sliding displacements on the opposing edges of a crack, respectively. Also highlighted the sensitiveness of this approach is to finite element refining. This displacement extrapolation approach successfully solved two mixed-mode issues [2].

Y.O.Busari , et.al did an accurate calculation of the stress intensity factor (SIF) and comparison of the critical strength of material (K_Ic) were used to determine the critical crack length of the specimen in an investigation on the rate of crack propagation and stress intensity factor for a typical fatigue (CT) specimen. Using computational techniques like displacement extrapolation and stress extrapolation applied close to the fracture tip, fatigue crack propagation were anticipated [3]. Behead V. Farahani , et.al considered an optical technique known as TSA for stress intensity factor determination in the suggested methodology hinges on a stress field acquired. Finite element technique calculations were used to confirm the validity of the experimentally obtained SIF solution. Positive outcomes from the computational study confirmed the validity of the SIF and stress field in relation to the experimental solution [8]. Saeed Reza Sabbagh Yazdi, et.al proposed a Galerkin Finite Volume Method (GFVM)-based modelling of two-dimensional linear crack propagation. [9].

Very few researchers have addressed the issue of enhance fatigue life due to impact load also very less investigation has happened on effective and efficient assessment of Stress Intensity Factor (SIF) through numerical approach. This research mainly focuses on extracting Stress Intensity Factor for In-plane Mode I loading and efficient utilization of local coordinate system displacement to extract accurate Stress Intensity Factor (SIF) computational. Enhancing the fatigue life of engineering components under service is one of the important criteria for efficient structural design. Currently the fatigue life of mechanical components is evaluated based on conventional fatigue life assessment criteria like Soderberg and Goodmaan condition which address the issue at macro level .There is a demand for analyze effectively fatigue life at micro level. To provide an efficient analysis of fatigue life on engineering components at micro level there is a need of understanding the manufacturing defect which act as stress concentration points and reduce the life of the components by setting converted by getting converted to small cracks by inside the components.

From the literature survey it has been found that while a lot of work has been done on the finding Stress intensity Factor by various Numerical Method Such as Stress and Displacement Extrapolation Method ,J- integral etc using Paris Erdogan Equation . Here a CT specimen is used under Mode I loading and compared Stress Intensity Factor while Impact load and Quasi static load . Hence evaluate the Critical Crack length at which the Stress Intensity Factor Matched with Fracture Toughness of the material.

OBJECTIVES AND METHODOLOGY

- To examine the compact specimen's stress intensity factor in accordance with ASTM standards.
- Using the Paris Erdogan equation to correlate the fracture toughness of the material with the fatigue life of a compact tensile specimen.
- Repeating the SIF for Mode I crack propagation for specimen subjected to Impact load
- Analyze the difference in fatigue life period for Compact tensile (CT) specimen subjected Quasi static load and Impact load.
- Validation of Stress Intensity Factor using Displacement Extrapolation Method.

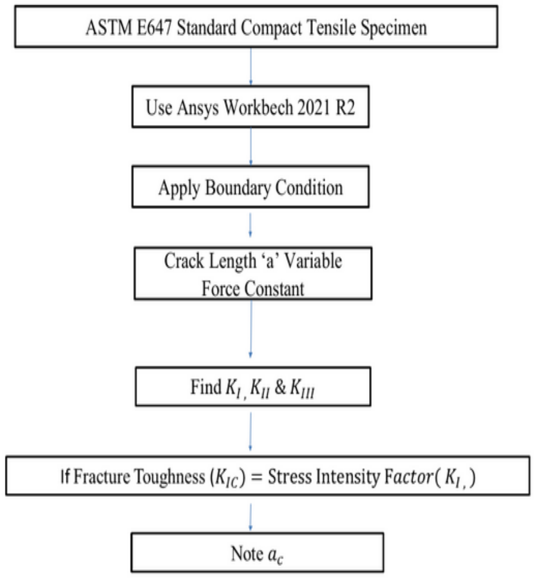


Fig 1: - Methodology to evaluate Fatigue Crack Growth Life

CRACK CLOSURE EFFECTS

Under cyclic loading, a crack develops as a result of alternating stress cycles. The crack begins to open throughout each stress cycle as the applied force rises and ends when the load falls. During the load-reduction phase of the cycle, the crack faces come into contact, causing the crack closure effect, which reduces the effective crack length. The stress intensity factor at the crack tip is substantially decreased by this contact between crack faces, which slows the growth of the crack. Additionally, the R ratio changes endlessly when the component is provided with variable amplitude.

The crack closure effect can offer a number of advantages, such as:

- Increased Fatigue Life: A component or structure's fatigue life might be greatly increased due to the reduced stress intensity factor near the fracture tip caused by crack closure. This is so because the stress intensity component has a significant impact on the rate at which a fracture grows.

- Increased Resistance to Failure: The fracture closure effect raises the stress intensity threshold factor necessary for crack growth. As a result, the material's overall structural integrity is improved because cracks must first experience greater stress levels before they can advance.

- Fracture Growth Slowed Down: The fracture closure effect really reduces the pace at which cracks grow. This can be helpful since it offers more time for safety precautions to be performed when maintenance or repairs are not possible.

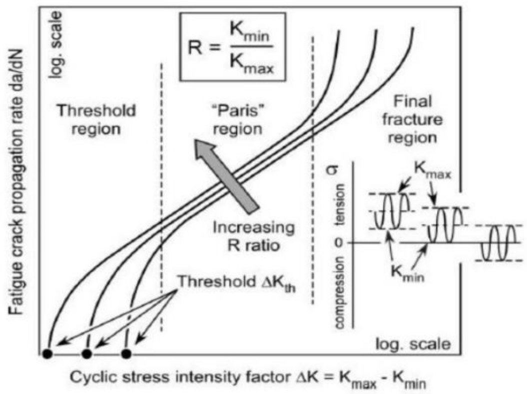


Fig 2: - R's impact on the da/dN- K curve when the crack closure effect is not taken into account.

When predicting the life of components that are sensitive to time-dependent crack development processes like fatigue or stress corrosion cracking, fracture mechanics frequently comes into play. If the fracture toughness is known, the critical crack size for failure may be calculated. The rate of cracking can be connected with fracture mechanics characteristics such the stress intensity factor. For instance, the empirical relationship shown below may often be used to illustrate the fatigue fracture propagation rate in metals.

$$\frac{da}{dN} = C(\Delta K)^m$$

OVERLOAD EFFECTS

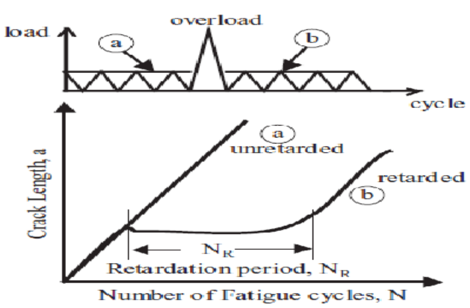


Fig 3: - Illustration of the overload effect

The "overload effect" is a phenomena where a material's resistance to crack propagation momentarily increases as a result of the application of a high load or stress, and it is used in the context of fracture mechanics. The plastic deformation and residual compressive stresses created near the crack tip during the application of the high load are to blame for this increase in crack resistance.A crack in a material serves as a focus of concentration for stress. The material's fracture toughness—a metric of its capacity to thwart crack propagation—may be exceeded as an external load is applied because the stress at the break tip gets concentrated and can do so. The crack may start to spread through the material if the applied load is large enough. However, in some circumstances, the material around the crack tip experiences plastic deformation if an exceptionally high load is given for a brief period of time and then removed. Remaining compressive stresses are produced at and near the fracture tip as a result of this plastic deformation. The tensile strains that encourage crack growth are offset by these compressive forces. Because of this, the fracture faces encounter compression rather than tension, which makes it more challenging for the crack to spread. This transient delay or pause in crack formation can be caused by this temporary increase in fracture resistance brought on by the overload effect. It's vital to remember that this effect is typically transient and is based on the unique loading circumstances and material characteristics. The overall fracture propagation behavior may not be affected by the overload if it is not severe enough or is sustained for a longer time. This is because the overload may not cause considerable plastic deformation and residual stresses.The overload effect has real-world applications in engineering and material design, especially when determining the dependability and safety of buildings with existing cracks. Engineers must think about how cyclic loading, different stress levels, and the possibility of overload events may affect a material's or structure's overall fracture behavior.

COMPUTATIONAL APPROACH

Finite element modeling refers, for the purposes of this definition, to the analyst's choice of the material models, finite elements (type/shape/order), meshes, constraint equations, pre- and post-processing options, governing matrix equations, and their solution methodologies within a selected commercial finite element analysis program. A very thin mesh of SINGULAR isoparametric pentahedral solid elements (SPENTA15) with user-specified number NS, length a from one crack face to another, and number of segments (NSEG) along the surface crack front make up the projected finite element model. The remaining portion of the domain is discretized using a compatible mesh of regular elements (NREG), namely isoparametric pentahedral solid element (PENTA15) and iso-parametric hexahedral solid element (HEXA20). There is a quick explanation of how these elements are created. The so-called Serendipity family's quadratic order hexahedral solid member is shown in Figure 3.1 There are 20 nodes in the element. The parent element, a bi-unit cube, has eight nodes at the vertices while the remaining nodes are at mid-side positions.

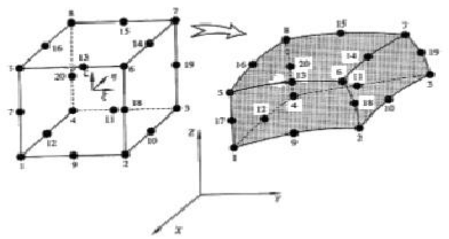


Fig 4:- Quadratic order hexahedral solid element

Figure3.2 depicts the pentahedral solid element of the serendipity family with 15 nodes. As seen in Fig. 3.2, this is created by further distorting the HEXA20 element. In particular, it entails collapsing a face and requiring the collocated nodes to have the same number of degrees of freedom. This element, known as PENTA15, is also utilized often.

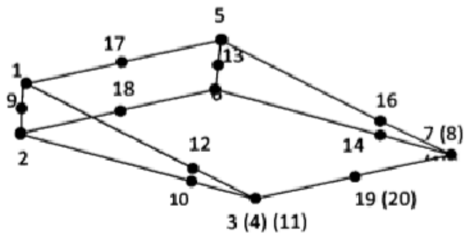


Figure.5 Singular pentahedral element

For computational fracture mechanics, a further distortion of the PENTA15 element yields the SINGULAR element SPENTA15 [Ingraffea et al. 1980]. In particular, a curving crack front runs down the edge with nodes 3-19-7. The mid-side nodes 10, 12, 14, and 16 have been relocated to quarter point positions that are nearer the crack front. To obtain convergence in the calculated stress intensity factors, it is possible to gradually increase the number of SPENTA15 elements (NS) from one crack face to the next and the number of segments (NSEG) along a crack front.

The remaining areas of the domain under inquiry are discretized using a suitable mesh of regular elements (NREG). Numerical trials are necessary to determine optimal values for NS, a, NSEG, and NREG for each issue in order to ensure convergence of estimated stress intensity factors.

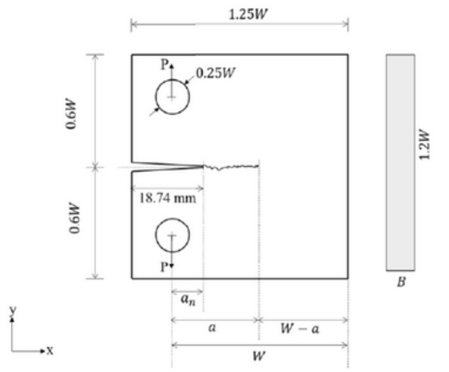


Fig 6: ASTM E647 Standard Compact Tensile Specimen Dimension

DISPLACEMENT EXTRAPOLATION METHOD

The nodal displacements around the fracture tip serve as the foundation for the displacement extrapolation method. According to Barsoum, Hensell, and Shaw, quarter-point isoparametric elements are employed to achieve a satisfactory approximation of the crack-tip field. By moving the midside nodes of all surrounding components a quarter to the fracture tip, the linear- elastic singularity for stresses and strains is achieved.

For a bi-dimensional crack subjected to mode I loading, the asymptotic equation for the displacement v normal to the fracture plane is given by

$$v = K_I \frac{1+\nu}{4E}\sqrt{\frac{2r}{\pi}}\left\{(2\kappa+1)\sin\frac{\theta}{2}-\sin\frac{3\theta}{2}\right\}+\frac{A_1(1+\nu)r}{E}(\kappa-3)\sin\theta \quad (1)$$
$$+\frac{A_2(1+\nu)r^{3/2}}{E}\left\{\frac{(2\kappa-1)}{3}\sin\frac{3\theta}{2}-\sin\frac{\theta}{2}\right\}+\ldots$$

where E is the elasticity modulus, n the Poisson's ratio, k the elastic parameter, Ai the geometry and load parameters, r and θ the polar coordinates, and k the elastic variable equal to 3-4ν for plane strain and (3-ν)/(1+ν) for plane stress. It is seen that the normal displacement at the crack tip, v (r =0), is zero as required by the symmetry of mode I.

Eq. (1) only contains components in r^1/2, r^3/2, r^5/2, etc. when the displacement v is assessed along the crack faces (), resulting in a more accurate extrapolation, as first indicated by Chan et al. [1].

When we specifically apply Eq. (1) to nodes A and B on the single element at the crack's top face (see

Fig. 1), we obtain:

$$v_A = K_I\sqrt{\frac{2}{\pi}}\frac{(1+\nu)(\kappa+1)}{4E}\sqrt{\ell} - \frac{A_2(1+\nu)(\kappa+1)}{12E}\ell^{3/2} + O(\ell^{5/2}) \quad (2)$$

$$v_B = K_I\sqrt{\frac{2}{\pi}}\frac{(1+\nu)(\kappa+1)}{2E}\sqrt{\ell} - \frac{2A_2(1+\nu)(\kappa+1)}{3E}\ell^{3/2} + O(\ell^{5/2}) \quad (3)$$

where l is the element side TB's length. For KI and A2, Eqs. (2) and (3) may be solved by ignoring higher order terms. The stress intensity factor's value is thus:

$$K_I = \frac{E}{3(1+\nu)(\kappa+1)}\sqrt{\frac{2\pi}{\ell}}(8v_A - v_B) \quad (4)$$

or

$$K_I = \frac{E'}{12}\sqrt{\frac{2\pi}{\ell}}(8v_A - v_B) \quad (5)$$

$$K_I = \frac{2E}{(1+\nu)(\kappa+1)}\sqrt{\frac{2\pi}{\ell}}v_A = \frac{E'}{2}\sqrt{\frac{2\pi}{\ell}}v_A \quad (6)$$

where E' is the effective elastic modulus denoted by E for plane stress and E= $1/(1-\nu^2)$ for plane strain. If components in $l^{3/2}$ and above are ignored in Eq. (2), a simplified calculation of KI may be constructed using the quarter node displacement, vA:

The term in $r^{1/2}$ of the displacement expansion along the top crack face can be matched with the corresponding term of the element interpolation function to generate a different estimation of KI.

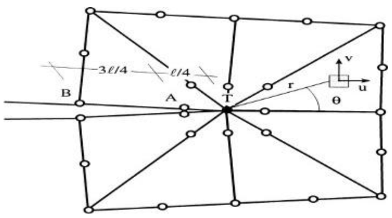


Fig 7:- Description of the Quarter Point unique elements and near crack tip field

The displacement field along the fracture edge for a single eight-node or six-node iso parametric element is dictated by the nodal displacements vA and vB and is given by

$$v(r) = (4v_A - v_B)\sqrt{\frac{r}{\ell}} - (4v_A - 2v_B)\frac{r}{\ell} \quad (7)$$

Setting θ = Π in equation (1) and finding terms with √r in equations (1) and (7) leads to the following result:

also, the current stress intensity factor is:

$$K_I = \sqrt{\frac{2}{\pi}}\frac{(1+\nu)(\kappa+1)}{2E}\sqrt{r} = (4v_A - v_B)\sqrt{\frac{r}{\ell}} \quad (8)$$

$$K_I = \frac{E}{(1+\nu)(\kappa+1)}\sqrt{\frac{2\pi}{\ell}}(4v_A - v_B) = \frac{E'}{4}\sqrt{\frac{2\pi}{\ell}}(4v_A - v_B) \quad (9)$$

Based on the nodal displacements of the quarter point element that is situated on the top face of the crack, Eqs. (5), (6), and (9) provide three different estimations of KI. A similar outcome would be attained for the bottom face piece due to symmetry.

RESULTS AND DISCUSSION

In the section that follows, we evaluate the performance of these three KI estimations. A notched sample is utilized to generate a fatigue fracture by using a laboratory fatigue test machine to apply cyclic loads through pins put into the sample's holes. The fatigue crack will begin at the site of the notch and run the length of the sample. The crack length is commonly assessed by measuring the compliance of the coupon, which alters as the crack grows longer. It can also be measured indirectly by attaching strain gauges to the back face of the coupon or by taking extensometer readings of the crack mouth opening in order to pinpoint the location of the crack tip.

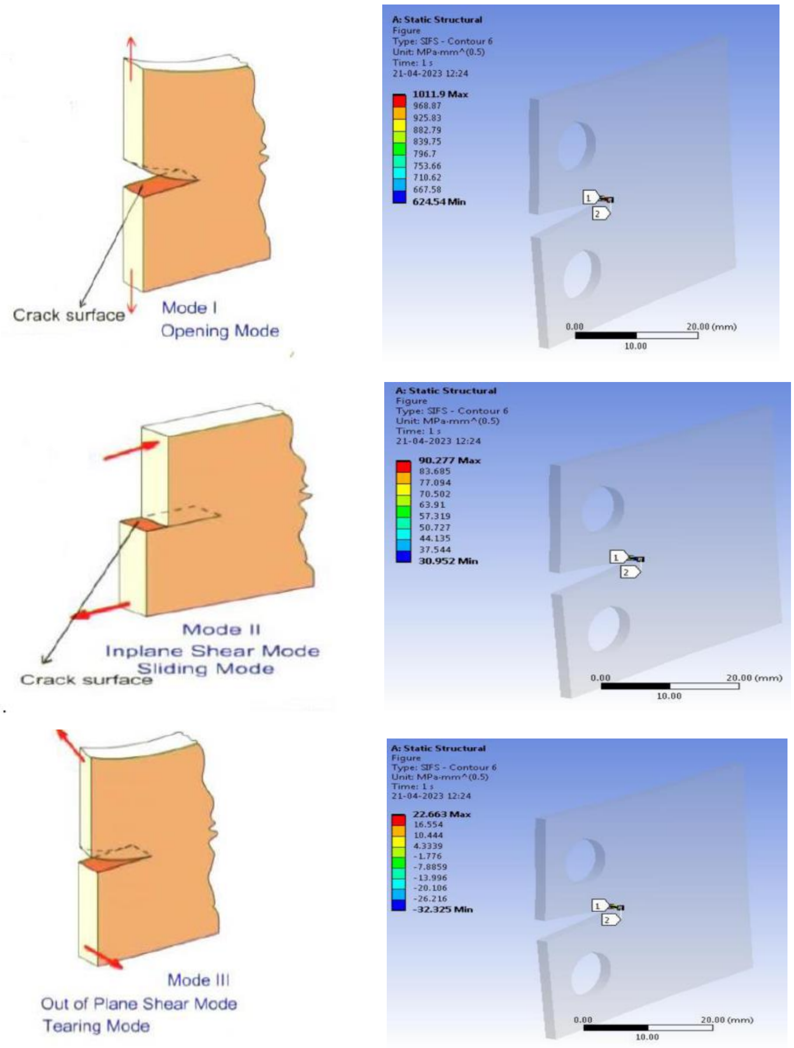


Fig 8: S*IF* results for all the three modes of crack propagation

The crack front, which was ignored in the plane stress example and taken into account in the plane strain case, is marked in the stressed model. In the graph of the stress intensity factor vs. crack length, the SIF value increases as the fracture length increases solely because the plastic zone around the crack tip expands. As a result, K1 rises and the barrier to crack propagation increases.

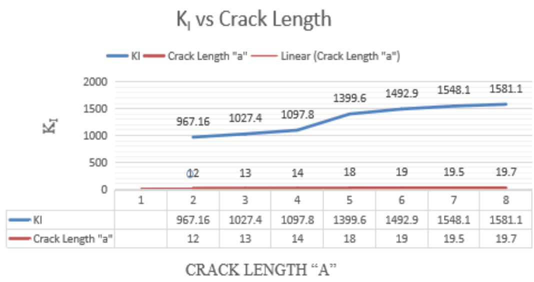


Fig 9: Results of K1 vs crack length

Similar depiction is shown for all the three SIF in different modes in the graph and it is clearly signifying that KI is dominant over other modes of crack propagation.

Fracture mechanics uses the stress intensity factor (K) to forecast the stress situation ("stress intensity") near the tip of a crack or notch brought on by a remote load or residual stresses. It is a key strategy in damage tolerance and a theoretical idea that is frequently used to describe a homogeneous, linear elastic material. It is crucial for developing a brittle material failure criterion. The concept can be applied to materials that exhibit slight yielding close to the crack's tip. Stress intensity factor also reached fracture toughness value as the crack length increased from 12 mm to the critical crack length of 19.7 mm. Once it passed the fracture toughness value, the material in the area of the tip started to propagate and fail.

Crack length 'a'(mm)	**K_I (MPa$\sqrt{m}$)**
12	967.16
13	1027.4
14	1097.8
18	1399.6
19	1492.9
19.5	1548.1
19.7	1581.1

Table 1: Compact Tensile Specimen Crack Length & Stress Intensity Factor

Using Paris- Erdogan equation 10 and the KI results, we may estimate the component's life by deriving the material constants for fatigue crack propagation using a sigmoidal curve. The stress ratio R and the variables K and da/dN determine the fracture propagation rate, which is given as.

$$\frac{da}{dN} = f(\Delta K, R) \qquad (10)$$

The nature of this link has been the subject of numerous investigations. They are empirical or somewhat empirical results. For many materials dependence of da/dN on R is not very significant, especially in Region II as shown as shown in figure below. Most designers are contented with the simple form. The final formation of eqn 10 after the integration from initial crack lenth to final crack length as

$$N_p = \frac{\ln\left(\frac{a_f}{a_0}\right)}{C f^2 (a_0 / W)(\Delta\sigma)^2 \pi} \qquad (11)$$

$$\text{We know that } a_c = a_f = \frac{K_{IC}^2}{[\pi (1.12 * \sigma_{max})^2]} \qquad \text{----------- (12)}$$

a/W	Crack Length 'a' (mm)	$\Delta K_{analytical}$	ΔK_{FEM}	ΔK_{Exp}	Dev % Exp & Analytical	Dev % FEM & Analytical	Dev % FEM & Exp
0.2935	11.94	873.87	887.12	887	1.50	1.51	-0.01
0.3185	12.94	933.10	972.53	976	4.59	4.22	0.35
0.336	13.44	974.98	1009.3	1089	11.69	3.52	7.89
0.3905	15.62	1122.43	1087.1	1252	11.54	-3.14	15.16
0.4415	17.66	1287.63	1272.6	1139	-11.54	-1.16	-10.49
0.49	19.60	1481.39	1454.8	1357	-8.39	-1.79	-6.72
0.4925	19.7	1606.12	1581.1	1364	-15.07	-1.55	-13.7

Table 2: Comparison of ΔK for Analytical, Displacement Extrapolation Method and Experimental

As depicted below, a line graph with data from experimental and finite element method data is plotted between the crack length (mm) in the x-axis and the stress amplitude in the y-axis.

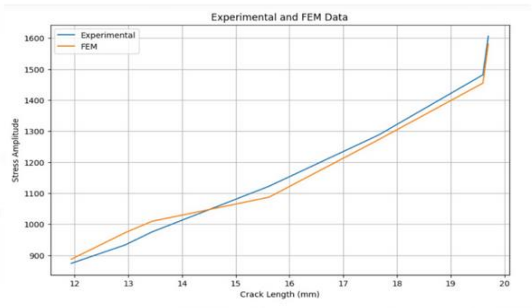
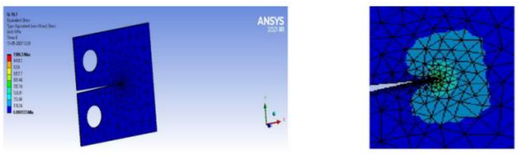


Fig 10: Graph Show Relation b/w Experimental & FEM

Enhancing the fatigue life of engineering components under service is one of the important criteria for efficient structural design. Currently the fatigue life of mechanical components is evaluated based on conventional fatigue life assessment criteria like Soderberg and Goodmaan condition which address the issue at macro level. From the graphs and tables is clearly showing the accuracy of Displacement Extrapolation Method for K1 result is more than the regular FEM results when compared with experimental values.



Equivalent Stress at Crack Tip   Plastic zone at crack tip

Fig 11: Graphical representation of plastic zone surrounding the crack tip

There is a demand for analyze effectively fatigue life at micro level. To provide an efficient analysis of fatigue life on engineering components at micro level there is a need of understanding the manufacturing defect which act as stress concentration points and reduce the life of the components by setting converted by getting converted to small cracks by inside the components.

CONCLUSION

Enhancing the fatigue life of an engineering components under service is one of the important criteria for efficient structural design. Currently the fatigue life of mechanical components is evaluated based on conventional fatigue life assessment criteria like Soderberg and Goodmaan condition which address the issue at macro level. There is a demand for analyze effectively fatigue life at micro level. To provide an efficient analysis of fatigue life on engineering components at micro level there is a need of understanding the manufacturing defect which act as stress concentration points and reduce the life of the components by setting converted by getting converted to small cracks by inside the components.

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