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An Experimental and Computational Investigation of Crack Growth Initiation in Compact Tension (CT) Specimen

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Abstract- An experimental and computational study of EN-31 steel Compact Tension specimen was performed. Compact Tension specimen was considered in the experimental portion of the study. Stress intensity factor, Crack tip opening displacement (CTOD) & J integral were main parameter found by the experimental analysis. Load vs CMOD graph are used to get the important parameter. The same parameters also investigated by the Finite element method for CT specimen. A comparison with a Experimental Vs Computational investigation on an EN-31 compact Tension specimen suggests similarities concerning the interaction between material nonlinearity and specimen response nonlinearity.

Index Terms- CTOD; J-integral; Stress intensity factor; Compact tension specimen; Abacus 6.10

I. Introduction

Fracture is a problem that society has faced for as long as there have been manmade structures. Fortunately advances in the field of fracture mechanics have helped to offset some of the potential dangers posed by increasing technological complexity. Researches in this field can help reducing the cost due to failure. The development of fracture mechanics started with Griffith's crack theory. Then many people did a lot of work in developing theories regarding fracture and its cause.Origin of such type of work is several centuries earlier. Experiments were performed by Leonardo Da Vinci, [3] that provided some clues as to the root cause of fracture. He measured the strength of iron wires and found that the strength is inversely related with wire length. The mechanics of fracture progressed from being a scientific curiosity to an engineering discipline, primarily because what happened to the Liberty ships during World War II. United States was supplying ships and planes to Great Britain under the Lend Lease Act. Under the guidance of Henry Kaiser, the United States developed a revolutionary procedure for fabricating ships quickly, known as the Liberty ship. It was a resounding success, until one day in 1943, when one of the ships broke completely in two parts while sailing between Siberia and Alaska. Subsequent fracture occurred in other Liberty ships. Out of roughly 2700 liberty ships built during World War II, approximately 400 sustained fractures, of which 90 were considered serious. About 10 broke completely [3]. Investigations started to find the causes of failure and its remedy. In the longer term structural materials were developed with vastly improved property against fracture. Also a group of researchers at the Naval Research Laboratory in Washington D.C. studied the fracture problem in detail. The field we now know as fracture mechanics was born in this lab during the decade following the War. This research group was led by Irwin. They extended the early works of Inglis, Griffith, and others. Mott extended the Griffith theory to a rapidly propagating crack. In 1956, Irwin developed the energy release rate concept, which is related to Griffith theory but more useful for solving engineering problems [3]. A lot of work has been done since then.

Major developments are:

- Irwin (1957) : K parameter. (Stress Intensity Factor)
  NRL [Naval Research Laboratory, USA] : Kc , Fracture toughness.
- Irwin (1960-61) : Small scale yielding (plasticity correction factor).
- Dugdale & Bareablatt : Plastic zone size.
- A. A. Wells (1963) : CTOD (crack tip opening displacement).
  K_{1c} test std. : 1973
- Rice (1968) : J – integral (Non linear elastic).
- Begley & Landes , USA(1971) : J_{1c} / J_c
- Burdekins & Dawes (1971) : CTOD design curve.
- Harrison etal (1975-76) : R-6 method.

II. Review of Literature

Degiorgi V. G , Matic, BAR-ON. P. I, Lee .G. M. C (1) have discussed An experimental and computational study of HY-100 steel three-point bend fracture specimens. Two specimens were considered in the experimental portion of the study, differing with respect to thickness and the presence of side grooves. Plane stress and plane strain finite element analyses of the specimens were conducted to assess the relative role of constraint on load vs crack opening displacement response and crack growth initiation. A critical value of the strain energy density associated with local material fracture was used to predict the onset of crack growth. The experimental responses were bounded by the predicted plane stress and plane strain load vs crack mouth opening responses. These results also provided an indication of the extent to which the side grooves in the thinner specimen provided more constraint than the thickness of the specimen without side grooves. A comparison with a previous investigation on an HY-100 compact fracture specimen suggests similarities concerning the interaction between material nonlinearity and specimen response nonlinearity.

Courtin. S, Gardin. C, Bezine. G, Ben Hadj Hamouda. H (2**)** A predictive method for remaining component lifetime evaluation consists in integrating the crack growth law of the material considered in a finite element step-by-step process. So, as part of a linear elastic fracture mechanics analysis, the determination of the stress intensity factor distribution is a crucial point. The aim of the present work is to test several existing numerical techniques reported in the literature. Both the crack opening displacement extrapolation method and the J-integral approach are applied in 2D and 3D ABAQUS finite element models. The results obtained by these various means on CT specimens and cracked round bars are in good agreement with those found in the literature. Nevertheless, since the knowledge of the field near the crack tip is not required in the energetic method, the J-integral calculations seem to be a good technique to deal with the fatigue growth of general cracks.

Zhu. G.P, Lee. G.M.C and Mufti. A.A (3**)** Crack initiation and stable crack growth under monotonic loading in steels has been studied using an elastic-plastic finite element analysis. The fracture criterion used for crack initiation and stable crack growth was the critical strain energy density. In addition the shift core method for the analysis of crack extension was used. In the shift core modeling method, crack advance is simulated by moving the coordinates of the core region which surrounds the crack tip, to obtain the stiffness reduction. Simultaneously the core itself geometrically undergoes a simple rigid-body motion or translation during the crack extension. The analytically calculated and experimentally measured load for crack initiation and the subsequent stable crack growth agreed well.

Wang. F, Lee. H.P, Lu. C (4) the present study introduces the concept of structural intensity, which can be interpreted as power flux, into fracture mechanics. It is derived theoretically that the normal component of the structural intensity along crack edge equals J integral. SI is the power flux or vector representation of the J-integral at the crack tip. Using the finite element method, the structural intensity can be easily calculated. The numerically calculated structural intensity is adopted to visualize the J-integral of a crack tip. Directional power flow path and magnitude at the crack tip is demonstrated schematically with the structural intensity, which facilitates convenient evaluation of the crack propagation status.

Gulleruda. A.S, Doddsa. R.H, Hamptonb. R.W, Dawickec.D.C (5) this work describes the development of two types of three-dimensional (3D) finite element models to predict stable, Mode I crack growth in thin, ductile aluminum alloys. The two presented models extend the standard 2D form of the Crack Tip Opening Angle (CTOA) methodology, which determines crack extension based on obtaining a critical angle at the crack tip. The more general 3D model evaluates the CTOA at each node along the crack front which enables the development of tunneled profiles.

Lam.P.S , Kim.Y , Chao. Y.J (6) Contrary to the previous work that successfully applied the constant CTOD/CTOA fracture criteria to relatively thin structures, this paper demonstrates that the initial non-constant portion of the CTOD/CTOA plays an essential role in predicting fracture behavior under plane-strain conditions. Three- and two-dimensional finite element analyses indicate that a severe underestimation of the load would occur as the crack extends if a constant CTOD/CTOA criterion were used. However, the use of a simplified, bilinear CTOD/CTOA criterion to approximate its non-constant portion will closely duplicate the test data.

Panontin. T.L, Makino. A, Williams. J.F (7) Improved formulae for estimating crack tip opening displacement (CTOD) from test records of compact tension (CT) specimens are developed. Two-dimensional, plane strain, finite element analyses of C(T) specimens are made for normalized crack depths, a/w , of 0.40-0.70 using Ramber-Osgood material behavior with strain hardening coefficients n = 5, 10, and 20. Finite element predictions of J, CTOD, crack mouth opening displacement (CMOD) and load are used to obtain proportionality constants relating the area under the load-$CMOD_{pl}$ curve to J_{pl}, and J to CTOD in terms of a/w and n. Improvements in CTOD estimates of 25% over existing estimation methods are obtained. Correction factors for displacements measured on the specimen front face instead of the load line are also examined.

Nikishkov. G.P, Heerens. J, Schwalbe. K.H. (8) A two-region empirical formula is proposed for the transformation of crack tip opening displacement (CTOD) δ_5 to the standard CTOD δ_{BS} and the J-integral. Coefficients of the approximation are fitted to data sets of three-dimensional elastic-plastic finite element solutions for plane side and side-grooved three-point bend and compact tension specimens. Solution parameters include also specimen size, crack front curvature and strain hardening of the material. The transformation of d_5 to δ_{BS} and J is implemented as a Java applet, which can be used remotely with the help of Web browser. A window for equality between CTOD δ_5 and CTOD δ_{BS} was defined.

Shia. Yaowu, Suna. Siying, Murakawab. Hidekazu, Uedab. Yukio (9) In this study the effects of weld strength mismatching and geometry parameters on the relationship between the J-integral and the crack tip opening displacement (CTOD) are investigated. Numerical analysis was carried out by an ABAQUS two-dimensional elastic–plastic analysis mode. The work was performed for center-cracked welded specimens with uniform tensile load.

HOFF.R, RUBIN. C. A and HAHN. G.T (10) this paper presents a new technique for simulating crack extension in conjunction with the finite-element method. The technique uses spring and gap elements to control the motion of nodes on the crack plane. These elements are available in many proprietary finite element codes, thereby obviating the need for a user-written finite-element code. Numerical results for stable crack growth are in excellent agreement with corresponding experiments. The technique is also applied to rapid fracture in ductile materials, as discussed in a companion paper.

III. RESEARCH METHODOLOGY

Stress Intensity Approach

A crack in a solid can extend in three different modes depending on the type of loading, Opening mode (mode I), Sliding mode (mode II), and Tearing mode. The superposition of all the three modes describes the general case of loading. Mode I is the most important one. The distribution of stresses, under both plane stress and plane strain conditions, can be obtained for region near the crack tip assuming that the size of the body is much larger than the crack size. The general expression for the stress intensity factor for mode I is given by

$K_I = \beta\sigma\sqrt{c}$ (3.5)

where 2c is the crack length and β is a dimensionless factor,

Which depends upon geometry as

$\beta = \beta(c/W, c/D, c/L)$ ----------- (3.6)

where W, D and L represents certain size parameters of the body. If there is a surface crack, then c represents the crack length. The stress σ in equation is a remote stress. The value of stress intensity factor at which crack extends is called critical stress intensity factor (denoted by K_C). A criterion can be established that unstable crack propagates when $K_C \geq K_{IC}$. (for mode I loading). Critical stress intensity factor can be determined experimentally or these values can be obtained from handbooks.

Later Irwin showed that the Griffith energy approach is equivalent to stress intensity factor (K) approach, within the framework of Linear Fracture Mechanics (LEFM). For predominantly linear elastic loading the relationship between K and G can be expressed as:

$$G_I = \frac{K_I^2}{E} \quad \text{(for plane stress)} \quad \text{------------- (3.7)}$$

$$G_I = \frac{K_I^2\left(1-\nu^2\right)}{E} \quad \text{(for plane strain)} \quad \text{------------- (3.8)}$$

Similar relationship can be given for mode II and mode III. The material property governing fracture may therefore be stated as critical stress intensity, K_C or in terms of energy as critical value G_C

Crack Tip Opening Displacement (CTOD)

The concept of CTOD (δ) came into existence by the independent works of Wells, Cottrell and Barenblatt [5] It is proposed that when a significant amount of plasticity occurs at the crack tip, the fracture process is essentially controlled by the attainment of a critical strain adjacent to the crack tip which can be measured be the CTOD. Dugdale postulated a strip yield model that gives a plastic zone size in plan stress for an ideal plastic non-strain hardening material. The CTOD for a centre crack specimen under tension has been obtained using Dugdale's model as

$$\delta = \frac{8a\sigma_y}{\pi E}\ln\sec\left[\frac{\pi}{2}\frac{\sigma}{\sigma_y}\right] \quad \text{-------- (3.9)}$$

Where σ_y is the yield stress, a is the crack size, σ is the applied stress, and E is the elastic modulus.

There have been a number of investigations relating plastic zone size and CTOD. At higher values of applied stress level the small scale yielding analysis may not apply. There is subsequent increase in CTOD value with the spread of plastic zone and crack growth preceding fracture. The elastic-plastic analysis has to be used to determine CTOD in these situations.

J – Integral

The concept of J-integral is based on an energy balance approach which are path independent by virtue of the theorem of energy conservation. This integral is applied to crack problems in homogeneous body of linear or non linear elastic material free of body forces and subjected to 2D deformation field so that all stresses σ_{ij} depend only on two Cartesian coordinates [14]. The J-integral is defined as

$$J = \int_\Gamma \left[w.dy - T_i \left[\frac{\partial u_i}{\partial x} \right] \right] ds \quad \text{------------------ (3.10)}$$

Where w is the strain energy density = $\int \sigma_{ij} d\varepsilon_{ij}$ (3.11)

T_i are components of the traction vector specified over a part of the surface of the body, u_i are the component of the displacement vectors and s is the distance along any contour Γ traversed in counter clockwise direction from the lower face of the crack around tip to the upper face. It has been that J is equal to the potential energy (PE) per unit crack extension per unit thickness (B),

$$J = -\frac{1}{B}\frac{d(PE)}{da} \quad (3.12)$$

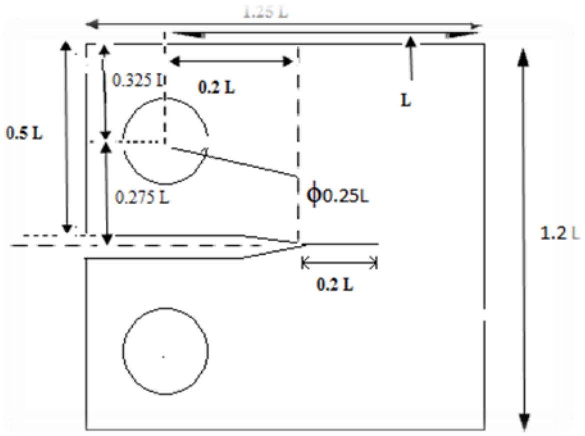
For an elastic plastic material, it can be interpreted as,

$$J = -\frac{1}{B}\frac{du}{da} \quad (3.13)$$

(3.10)Which represents the rate of elastic and plastic work done with respect to crack length (the dissipation energy rate). Thus in EPFM, the use of eqn.(3.13) relies not on energy balance but on path independence and the degree to which the value of J is related to a singularity of stress and strain in the crack tip region.

IV. Experimental Analysis

The CT specimens were machined from the rolled plate maintaining an L-T orientation the longitudinal or the rolling direction was kept perpendicular to the notch plane and the crack propagation direction along the transverse direction. The dimensions of the CT specimen were kept as per the ASTM standards as shown in figure 1.1. The specimen and the notch orientation are shown in figure 5.1 for the CT specimen. The specimens of 7 mm thickness were machined from plates of available material. The width of specimens taken is 50mm. The other dimensions as specimen length, hole diameter were maintained as per the ASTM standards. The specimens were polished for better crack visibility.



(Figure 1.1)

Load Calculation for Pre-cracking

a_0 = 23.745 mm
a = 26.745 mm
W = 50.06 mm
α = 0.534
B = 7.18 mm
K_{max} = 15 $MPa\sqrt{m}$

The K_{max} is given by the following equation for the CT specimen.

$$K_{max} = \frac{P_{max}(2+\alpha)}{B\sqrt{W}(1-\alpha)^{1.5}}(0.886 + 4.64\alpha - 13.32\alpha^2 + 14.72\alpha^3 - 5.6\alpha^4) \qquad (5.1)$$

Where, P_{max} is the maximum value of load, B is the specimen thickness, W is the width and the factor α = a/W where 'a' is the crack length.

Plastic CTOD, $$\delta_p = \frac{0.46(w-a_0)V_p}{0.46w + 0.54a_0 + (C-w)}$$ = 0.7755 mm

Elastic CTOD, $$\delta_e = \frac{K_I^2(1-\nu^2)}{m\sigma_y E}$$ (where, m = 2 for plane strain)
= 0.0334 mm

So, Total CTOD, **δ_c = 0.809 mm**

Now, $$J = J_{el} + J_{pl}$$

Where $$J_{el} = \frac{K_I^2}{E}$$

And $$J_{pl} = \frac{\eta_p U_p}{B(w-a_0)}$$

where, $$\eta_p = 2 + 0.522\left(1 - \frac{a_0}{w}\right) = 2.2744$$

U_p is the plastic energy associated with corresponding LPD.
At critical load, P=15600N, U_p = 30.25 Nm
So J_{el} = 19.0999 KJ/m^2
And J_{pl} = 214.653 KJ/m^2
So, Critical J-integral, **J_{IC} = 233.753 KJ/m^2**

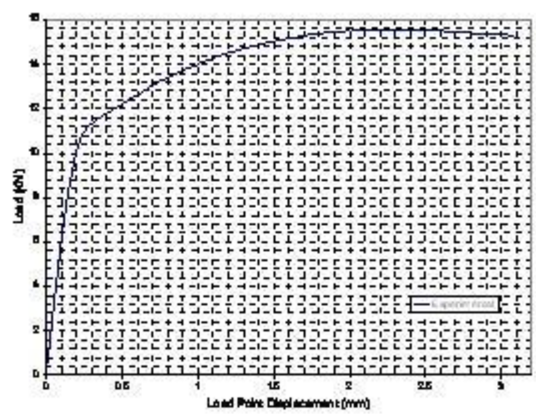


Fig 1.2

Experimental Analysis			
Crack Length (Δa, mm)	**CTOD (δ, mm)**	**J-integral (J/m^2)**	**Cumulative Crack Length (Δa, mm)**
0.62	0.069659	30460.85	1.5
1.80	0.184675	55814.96	2.1
2.38	0.271633	90231.19	2.8
3.17	0.389913	143814.5	3.6
3.87	0.52341	163423.0	4.3
4.45	0.593351	199247.6	5.1
5.31	0.701468	233753.9	6.0
5.85	0.808883		

Table No.1.1

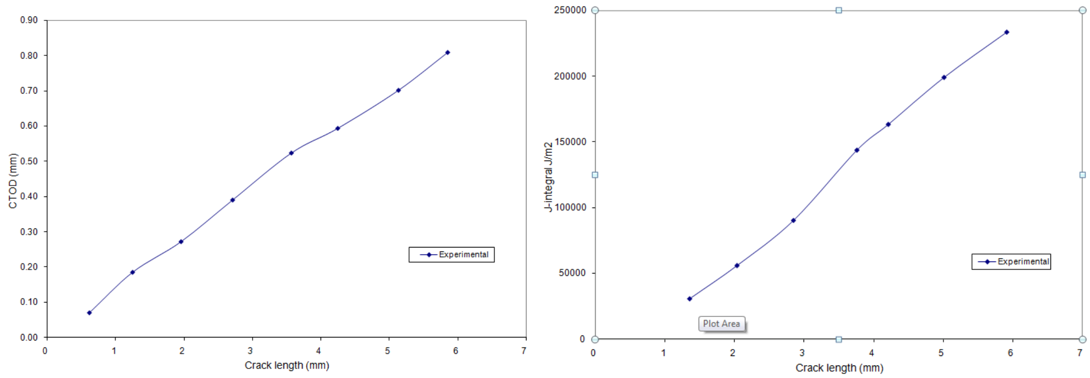


Fig No 1.3

V. Simulation Work

The ABAQUS finite element system includes:

- ABAQUS/Standard, a general-purpose finite element program.
- ABAQUS/Explicit, an explicit dynamics finite element program.
- ABAQUS/CAE, an interactive environment used to create finite element models, submit ABAQUS analyses, monitor and diagnose jobs, and evaluate results.
- ABAQUS/Viewer, a subset of ABAQUS/CAE that contains only the post processing capabilities of the Visualization module.

It is suitable for modeling transient dynamic events, such as impact and blast problems, and is also very efficient for highly nonlinear problems involving changing contact conditions, such as forming simulations.

The different modules in ABAQUS package are

- Part
- Property
- Assembly
- Step
- Interaction
- Load
- Mesh
- Job
- Visualization
- Sketch

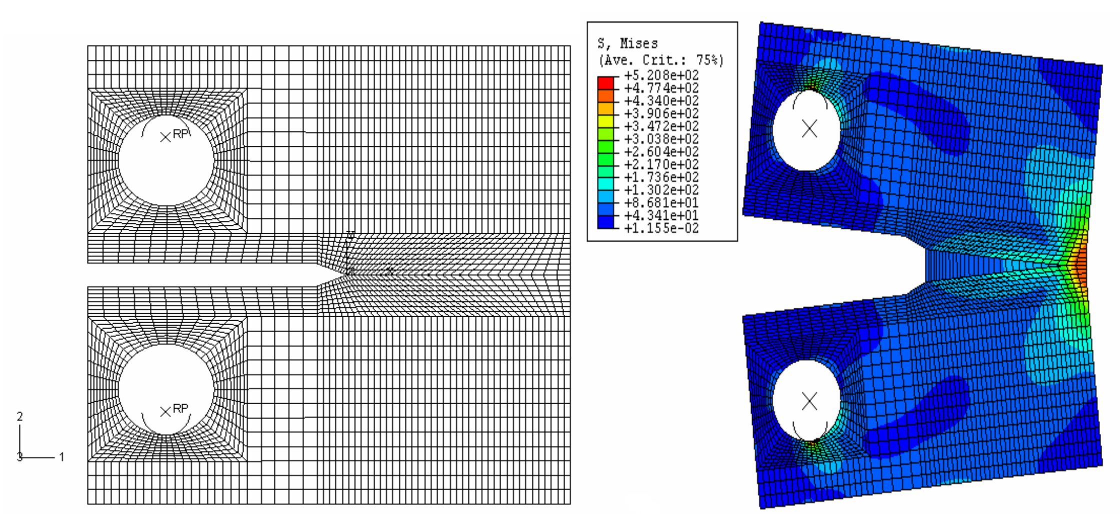


Fig 1.4: After Fracture and before fracture

Simulation data			
Cumulative Crack Length (Δa, mm)	**J-integral (KJ/m^2)**	**Crack Length (Δa, mm)**	**CTOD (δ, μm)**
1.36	30460.85	1.1	0.205
2.04	55814.96	1.8	0.285
2.85	90231.19	2.4	0.357
3.76	143814.5	3.2	0.438
4.21	163423	3.7	0.491
5.01	199247.6	4.1	0.552
5.91	233753.9	4.9	0.672
5.93	283753.9	5.5	0.75

Table No 1.2

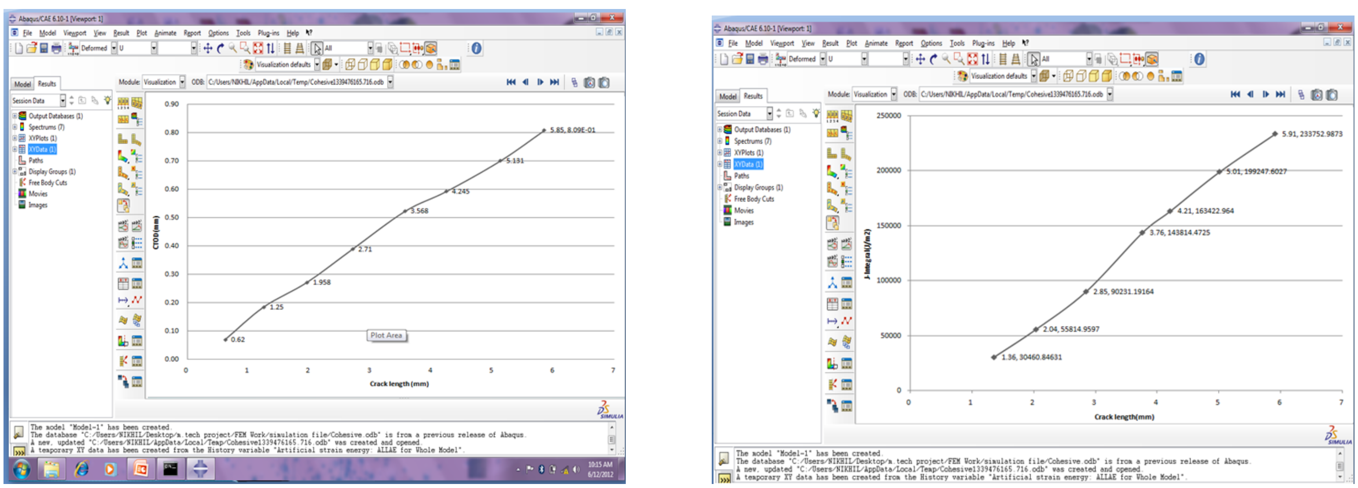


Fig. No 1.4

VI. Validation of Results

Comparison of CTOD resistance curve between experimental results and FEM analysis results.

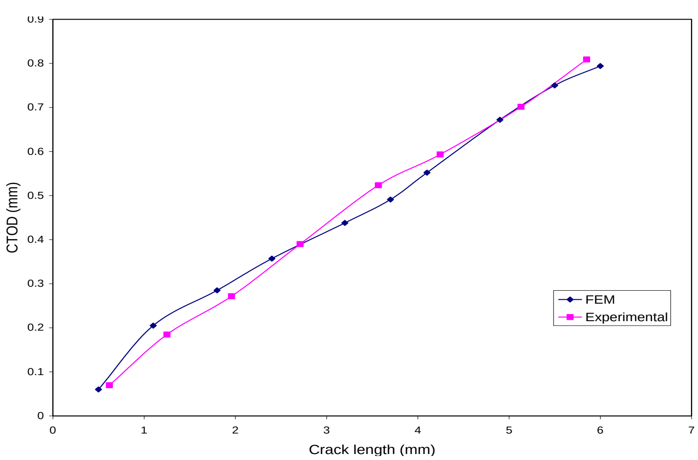


Fig No 1.6

Comparison of J-Resistance curve (J-R curve) between experimental results and FEM analysis results

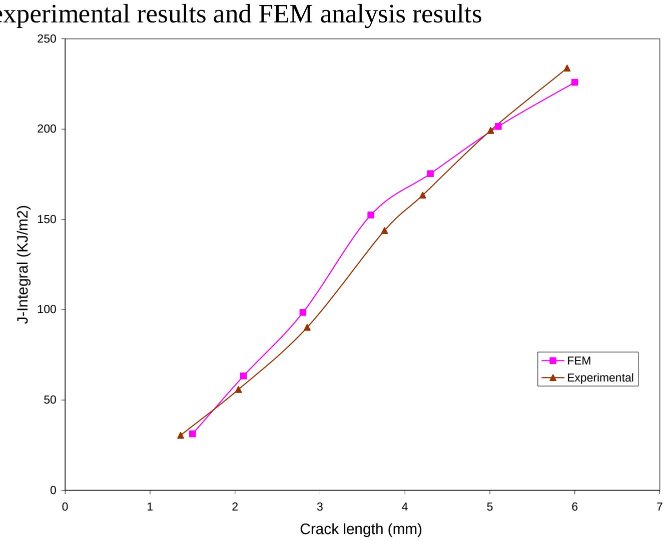


Fig No.1.7

VII. Conclusion

The presents paper present the experimental and numerical simulations on compact tension specimens, for the determination of fracture toughness parameter and crack growth resistance curve. The important conclusions drawn from the present work are as follows:

1. Fracture toughness in terms of critical CTOD and critical J-integral are obtained in EN31 steel by finite element analysis and also by experiments. δ and J Resistance curve are also obtained. The values are as follows:

For CT specimen, $\delta_c = 0.75$mm and $J_{IC} = 225.867$ KJ/m^2
(Finite element analysis)
$\delta_c = 0.8088$mm and $J_{IC} = 233.754$ KJ/m^2
(Experimental analysis)

2. It is found that the numerical simulation of practical problems is very useful. Results of numerical analysis are reliable as they are comparable with the experimental results obtained. The time and money can be saved by skipping expensive experimentation in this way. Also the failure incidents can be avoided by conducting the analysis prior to actual usage.

3. It is noticed that J-integral method has some advantages compared to displacement interpolation as the knowledge of exact displacement field near the crack tip is not required. J-integral can be directly extracted from Abaqus analysis. Also J-integral is a more general fracture toughness parameter as it can be applied to both linear and nonlinear situations.

4. Analysis of CT sample is done using cohesive element to model the crack. An inverse method is adopted to find out the properties of cohesive element by comparing it with another FE simulation.

VIII. Recommendations for Further Work

The recommendations for further work include the following:

1. To carry out the analysis for other different standard specimens.
2. To carry out the analysis of both the specimen using cohesive elements and get δ-R curve along with variation of reaction force as a function of displacement.
3. Carry out experiments on Compact tension specimen to validate the results obtained by numerical simulation.
4. To find out properties of cohesive elements (like G_{IC}) by conducting experiments and implement these properties into numerical simulation for finding stable crack growth

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