FCG Studies in Pressure Vessel Design using C40 Steel Arc Shaped Specimen

Mahantesh Matur
Department of Mechanical Engineering
M.S.Ramaiah Institute of Technology, Bangaluru

V. Krishnan
Department of Mechanical Engineering
Sir M. Visveshwaraya Institute of Technology, Bangaluru

P. Dinesh
Department of Mechanical Engineering
M.S.Ramaiah Institute of Technology, Bangaluru

Abstract

Presence of initial cracks and their subsequent growth under repetitive loading leads to catastrophic failure of the pressure vessels. To investigate failure of such pressure vessels due to the presence of small circular notch as initial flaws , an arc shaped tension specimen having notch on the inner surface is used in the present study of Fatigue crack growth (FCG). C40 steel specimen with 4 mm notch length is prepared as recommended by ASTM-E399 standard. Fatigue crack growth test has been carried out as per the procedure recommended by ASTM 647-08. A constant amplitude cyclic loading with load range $\Delta P =$ 4.55kN was applied at room temperature. FCG rate thus obtained experimentally is compared with FCG rate obtained by FEA using Paris' law. The values are in close agreement. The study shows the dependency of crack propagation on the stress intensity range induced the material.

Keywords: C40 (En8 Steel), Arc Shaped Specimen, Fatigue Crack Growth, FEA, Notch

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I. INTRODUCTION

C40 is usually supplied untreated and is a very popular grade of through-hardening medium carbon steel, which is readily machinable in any condition.

Applications of such steel are in, as brackets, bushes, studs, crankshafts, connecting rods, rings and flanges, railway couplings and axles undergoing fatigue loading. It has been found that often structures fail, even when load is well within the yield stress.

Although designers give more importance to design featuring, notches [1], complexity of specimen geometry [2] and groves [3] to minimize the stresses, premature failure of the components repeatedly takes place during the service.

Hence it is necessary to understand the mechanism of fatigue crack growth in a material, through the tests using the suitable experimental setup. FCG tests are classified in numerous ways. If the stress that varies throughout the cycle is in between constant values, then it is called as constant stress amplitude test and if not then, it is called as variable amplitude test. The constant amplitude test is further divided into three types, namely routine test, short life test and long life test. If the number of cycles the specimen or component subjected to $\leq 10^6$ cycles, then the test is called as short life test. If the number of cycles the specimen or component subjected to $\geq 10^6$ cycles, then the test is called as long life test.

The crack that is likely to grow under given loading condition can be analyzed through several approaches. They are stress approach, displacement or energy methods [4,5]. Varieties of cracks have been observed in the components because of wrong methods of manufacturing practices such as surface cracks, embedded cracks and edge cracks.

Both the surface and embedded longitudinal radially propagating cracks in thick cylinder under internal pressure was studied and it was verified analytically that crack depth has more influence on the drastic failure of the structure than the crack length [6]. Experimental work to study the FCG in C -shaped specimen to represent real pipe structure and CT specimen with different crack geometries revealed a good correlation between the two specimens for the Paris' law [7].

A Finite element method to solve the fracture problems. Crack opening displacement approach to extract mixed mode SIF(s) has one disadvantage in 3D crack problems that a state of plane strain or plane stress must be assumed initially. To circumvent this problem a method was proposed called the nodal force method and was applied to a semicircular surface crack in a finite thickness plate under remote tension [8]. SIF at an external elliptical part through surface crack located at double curvature zone of the pipeline under internal pressure has been studied. Tendency of SIF increment with increase of relative curvature below the flaw was observed particularly for low aspect ratio and more relative crack depth. Also key point noted was comparatively, longitudinal flaws were more dangerous with higher SIF registered than the transverse flaws [9,10].

In the present study, it is proposed to study the crack propagation in an arc shaped tension (AT) specimen made up of C40 steel, by conducting FCG test. The result of FCG test gives SIF range (ΔK) and the number of cycles for failure. Also, ΔK is obtained by using FE technique, where SIF is extracted by the quarter point method. Correlation between SIF range so obtained from experiment and FEA was established against the crack length. Using Paris law [11], number of stress cycles required before final fracture of the specimen was evaluated and compared with FCG results with good agreement .

II. EXPERIMENTAL STUDY

In this section brief explanation regarding the material, specimen geometry and test method employed in studying the fatigue crack growth behaviour of C40 Steel in the presence of notch is presented.

A. Material and Details of specimen

Specimen raw material is extruded bar of 160 mm diameter and length 150 mm. An arc shaped tension specimen as shown in figure 1 is produced from the bar and the stages of manufacturing are as shown in figure 2 (a-d). Specimen geometry of CR orientation (as per the crack plane orientation code suggested by ASTM E-399) is used for the present study. The notch in the specimen is 4 mm in length with nose radius of 0.25 mm is cut by wire Electric Discharge Machining.

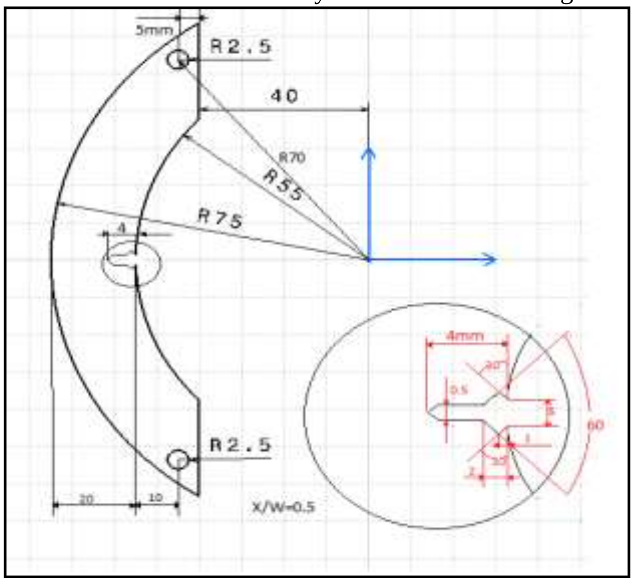

Fig. 1: Specimen geometry

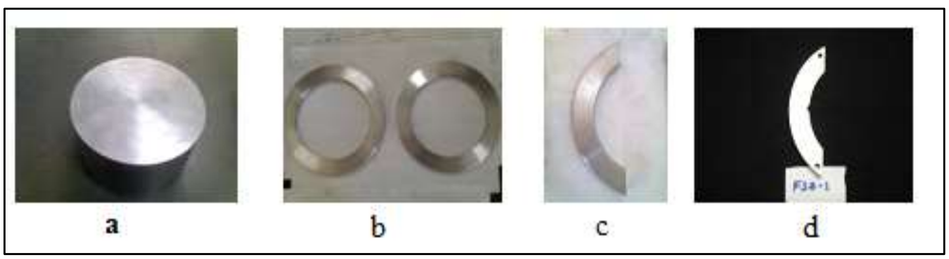

Fig. 2: (a –d) Raw material up to final specimen geometry

B. Testing Procedure

Fatigue crack growth test has been carried out as per the procedure recommended by ASTM 647-08, using the hydraulic actuating fatigue testing machine of 25 kN capacity. A constant amplitude cyclic loading with a sinusoidal wave form at a frequency of 10Hz, load ratio R=0.3 and load range ΔP= 4.55 kN was applied at room temperature. Loading ratio, x/ w of 0.5 was used in the present study, where x is the distance from the point of loading to the crack face in the horizontal direction and w is the width of the specimen, shown in figure 1. The experimental setup is as shown in figure 3. The resulting crack propagation in the width direction of the specimen is recorded. The crack growth, a as a function of number of stress cycles N, represented by means of a- N graph is obtained from figure 4. Fatigue crack growth rate, da/dN versus ΔK, characterizes a material's resistance to stable crack extension under cyclic loading. The crack growth rate as a function of stress intensity factor range is plotted using the experimental results as shown in figure 5.

These results were fitted according to the Paris law[12]; $da/dN = C(\Delta K)^m$, where C and m are experimental constants obtained from fitting curve. To determine Paris constant, a curve with a minimal deviation from all data points is desired. This best fitting curve can be obtained by the method of least squares. R^2 is a goodness of fit of linear regression, which ranges between 0.0 and 1.0. After many trial, the best curve fit is obtained , which gives the C and M values as 3e-10 and 3.929 [18].

Fig. 3: Experimental setup

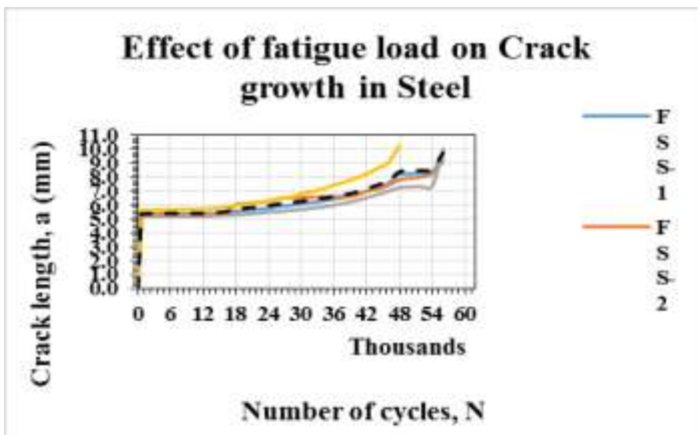

Fig. 4: Crack growth curve

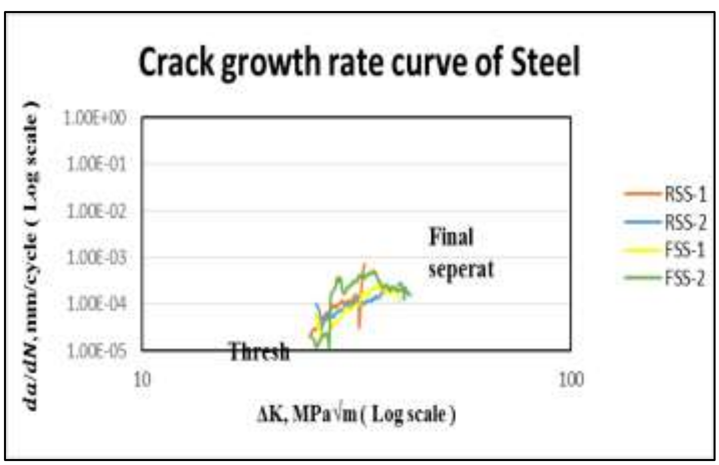

Fig. 5: Fatigue crack growth rate curve

C. *Finite Element Analysis*

A three dimensional (3D), finite element analysis (FEA) is carried out using ANSYS software with plane strain assumptions. The geometry of the arc shaped tension specimen with notch is as shown in figure 1. The geometries were meshed with two element types, quadratic elements for 2D modelling and Hexahedral element for 3D modelling. Modulus of elasticity and Poisson's ratio of 210 GPa and 0.3 respectively were used as material properties. To resolve crack tip stress fields at the key point, that is singular elements at the crack tip [4,13], a sufficiently fine mesh of 0.05 mm at the crack tip radius was incorporated and the same with other details are as shown in figure 6.

All degrees of freedom were constrained to zero at the lower part of the specimen at the hole, and the tensile load was applied at the upper part of the specimen.

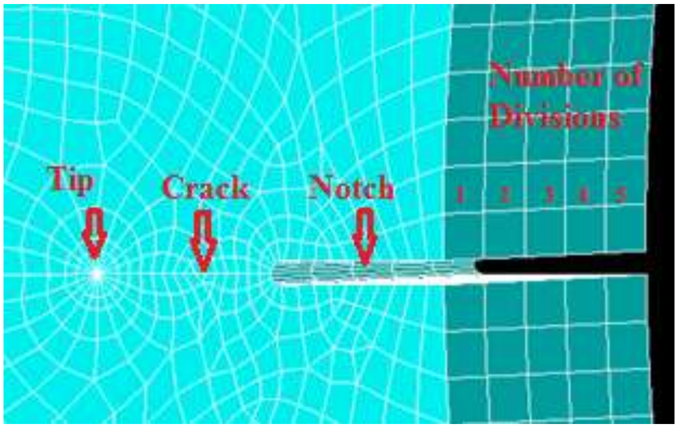

Fig. 6: Finite element mesh with notch and crack

III. RESULTS AND DISCUSSION

The strength of the elastic stress field around the crack tip is determined by finding the SIF. The finite nodal solution so obtained provides the maximum SIF, i.e. K_{max} corresponding to maximum load and the process is repeated for minimum load to obtain minimum SIF, K_{min}. The process is continued up to the stage when K_{max} researches K_{IC}, the critical SIF. Difference between maximum and minimum SIF were calculated and compared with the data directly from the experiment.

A. ΔK vs Crack length

Fatigue crack growth behaviour depends mainly on two stress intensity fracture mechanics parameters, i.e. ΔK and KI_{max}. Stress intensity range, ΔK explains fatigue damage, whereas KI_{max} for the crack tip widening. Figure 7, gives the characteristic relationship between crack length and stress intensity range for experimental and FEA results.

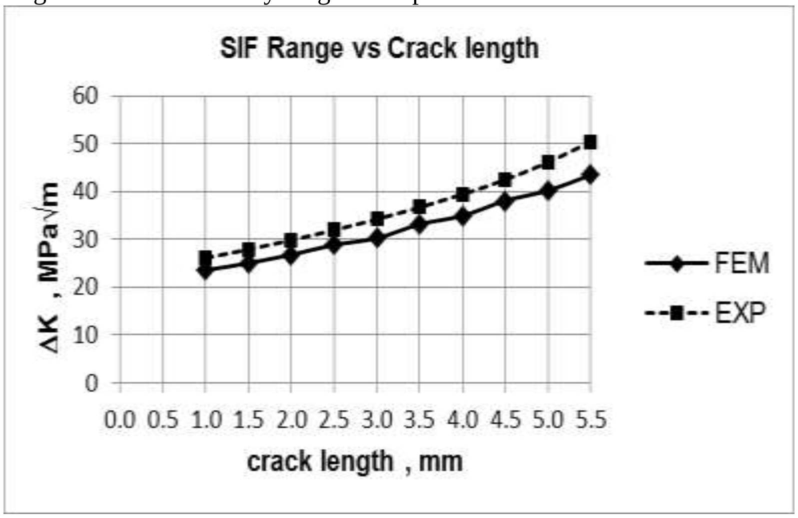

Fig. 7: Characteristic relation between crack length and stress intensity range.

The results show the dependency of the crack propagation on the stress intensity range of the Steel material [14]. It is observed from the experimental results that, there exists some ΔK value that helps in the nucleation of crack and at K_{max} of 26.11 MPa√m, crack has grown by 1 mm. That is, initially stresses at the tip of the notch are high, which cause intensive plastic deformation in the plastic zone. Thus from the initial notch of 4 mm, total widening of the notch reaches to a length of 5 mm. But, at this point of time material is still safe as it can resist the further load on it. Material weakening continues as the auxiliary load continues on the material, leading to the fatigue damage at K_{max} of 46.11 MPa√m. By this time, stable crack resistance of the material has been reached, as crack grows to 5 mm (total widening of the crack is 9 mm from inner surface). Finally due to instability specimen fails, at the stress range of 50.44 MPa√m. Finite element analysis prediction of crack growth due to fatigue damage shows the same trend and agrees well with experimental results.

B. FCG Calculation

Using the Paris constants so obtained from the experiments, fatigue crack growth rate is computed. The number of cycles required for the crack propagation up to the failure is calculated using the integral form [15,16] :

$$\int_{ai}^{af} \frac{da}{C(\Delta K)^m}$$

Note that the number of stress cycles for crack initiation is not included in the total life cycle of the specimen under consideration. The same procedure is repeated for the arc shaped tension specimen without any notch. Table 1. gives the number of fatigue cycles , so obtained from experiment and FEA.

Table - 1
Comparison of Fatigue cycles from FCG Test and FEM

Crack length	*Total Cycles*		
	EXPT	*FEA*	*% ERROR*
1.0	*10867*	*13494*	*19.47*
1.5	*21679*	*24168*	*10.30*
2.0	*28488*	*32353*	*11.95*
2.5	*33341*	*38454*	*13.30*
3.0	*37828*	*43525*	*13.09*
3.5	*41229*	*47056*	*12.38*
4.0	*43689*	*49934*	*12.51*
4.5	*45824*	*51987*	*11.85*
5.0	*46462*	*53641*	*13.38*
5.5	*46792*	*54860*	*14.71*
		AVG:	*13.29*

As the last stage of the crack growth is reached, ΔK is maximum and crack growth rate is extremely high with little fatigue life cycles. Thus initial notch of flaw dimension affects the life of the specimen more than the effects of dimensional change or pressure change [17]. Experimental results, shows that the number of stress cycles required for the crack to propagate from the initial notch, up to the failure of the material, are 46792 cycles. Whereas FEA results show the same trend, and specimen to fail at 54860 cycles with a reasonable error.

IV. CONCLUDING REMARKS

In this study, Fatigue crack growth characteristics of notched specimen of C40 steel have been studied, both experimentally and numerically. It is found that crack propagation from the notch is function of stress intensity range of the material. Crack tip widening from the notch requires, a maximum stress intensity of the order of 26.11 MPa√m. Material weakening progresses as the fatigue loading continues, leading to the fatigue damage at K_{max} 50.44 MPa√m. The results of the study show that the specimen with notch cannot resist, higher stresses and fails at fewer fatigue life cycles. There is good agreement of fatigue life obtained between the FCG and FEA results.

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