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Evaluation of Stress Intensity Factor and fatigue life for Mixed-Mode crack propagation in Drive Shaft of an All-Terrain Vehicle

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Abstract

A drive shaft is a mechanical component for transmitting torque. It is subjected to repeated torsional loading which reduces its life. This paper aims at the estimation of fatigue life of drive shaft considering the stress intensity factor calculations for a half-elliptical crack subjected to torsion loading. Finite element analysis is used to ascertain the crack region to determine the stress intensity factor for various crack-lengths. The software used for the analysis is ANSYS 14.5 [WORKBENCH]. The reliability of the software has been proven using a benchmark problem. The stress intensity factors are presented and observed along the crack front. The critical stress intensity factor based on the fracture toughness of the material is obtained. The stress intensity range obtained was employed to predict fatigue crack growth behaviour and fatigue crack life estimation by using Paris law. It is found that for a critical crack length of 5.72mm, the crack growth rate is 6.8E-6m/cycle and fatigue life cycles to failure is 11.2 million cycles.

1. Introduction

A drive shaft is a mechanical component for transmitting torque and rotation, usually used to connect other components of a drive train that cannot be connected directly because of distance or the need to allow for relative movement between them. They are subjected to torsion and shear stress. During each operation, there is a certain amount of permanent damage induced in the shaft. This could ultimately lead to fatigue failure. Such a failure, if not predicted, can result in catastrophic damage leading to loss of both human and property.

Further, failure of a material can be broadly classified as fracture, fatigue or creep. Fracture refers to the failure of a structure by means of propagation of a crack, breaking it into more than one different part. Fracture of any component can be classified as opening, sliding or tearing on the basis of the displacement of the crack. The fracture toughness of a specimen can be measured through the following parameters- Stress Intensity Factor (K), Energy Release Rate (G), Path independent integral (J) and Crack Tip Opening Displacement (CTOD).

Different problems in fracture mechanics can be solved by two different approaches, on the basis of the nature of the material of the specimen.

They are:

1) Linear Elastic Fracture Mechanics (LEFM)
2) Elastic Plastic Fracture Mechanics (EPFM)

For this paper, LEFM is the approach employed to evaluate the stress intensity factor near the crack tip. In LEFM, analysis is developed with little regard for plastic zone at the crack tip. This means that LEFM is used only for brittle materials. Consequently, the analysis of brittle materials is far simpler than the analysis of the material having a plastic zone at the crack tip.

There is another advantage of finding solutions to elastic crack problems. In many real life cases where plastic zone size is quite small in comparison to crack length, the influence of plastic zone in the elastic analysis may be neglected. That is, if stress fields in such cases are determined for purely elastic and elastic-plastic cases separately, the difference between the two is small enough to be neglected. An exhaustive survey of methods for three dimensional analysis of cracked solids and structures is presented by Raju and Newman in [1]. An up to date survey and assessment of published literature identifies the finite element method in general and a commercial FEA software in particular

for fracture mechanics analysis of solids and structures with surface cracks.
The CAD model of the drive shaft is shown in the figure1.

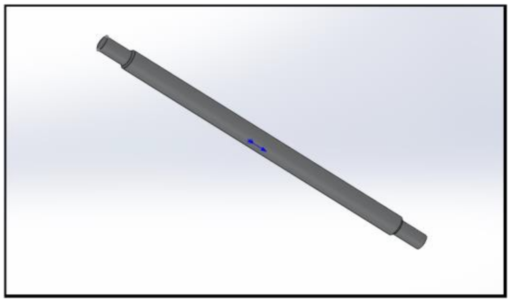

Figure 1. CAD Model of drive shaft

1.1 Material Properties

The widely used material for drive shaft is Alloy Steel-4340 because of its high strength. The material properties considered at room temperature are given in the table 1.

Table 1. Material properties

Material	Alloy Steel 4340
Yield strength	2015 MPa
Tensile strength	2214 Mpa
Fracture toughness	50 MPa√m
Density	7.84 g/cm³
Diameter	25 mm

2. Methodology

Geometric modelling of the drive shaft of an ATV was done using SOLIDWORKS. Meshing was done by using tetrahedron type of element in ANSYS mesh tool. Loading and boundary conditions were applied to the drive shaft to ascertain the critical region or crack zone of the shaft. Further, crack was introduced in the critical region of the drive shaft. Semi-elliptical crack geometry in the crack zone for various crack lengths was initiated till stress intensity factor for mixed mode condition near the crack tip exceeded the fracture toughness of the material. Fatigue crack growth rate and fatigue crack propagation life cycles were then calculated using Paris equation which is given below

$\frac{da}{dN} = C(\Delta K)^m$ … C and m are material constants

C=6.8E-12 ; m=3.0 for the selected material.

$\Delta K = K_{max} - K_{min}$

The number of fatigue life cycles to failure was calculated by the following equation

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

3. Benchmark Problem

In order to validate the obtained stress intensity factor solution, a benchmark problem whose solution is available in literature [4] has been solved by using fracture module in ANSYS. The analysis of rectangular flat plate specimen having a breadth of 25.132mm, width of 20mm and height of 40mm is conducted on ANSYS and the results of the analysis are verified with the results obtained from the literature [4]. The model with crack is shown in the figure 2.

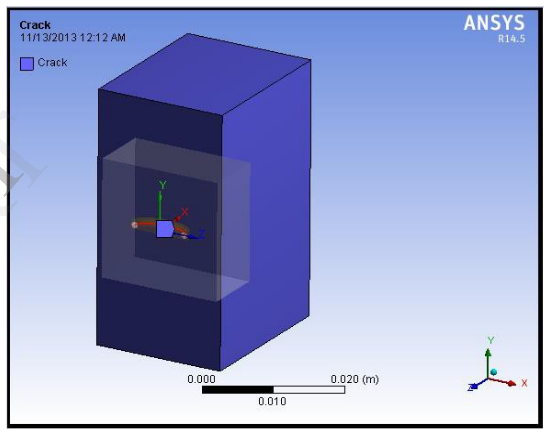

Figure 2. FE Model of benchmark problem

The result of analysis is plotted in figure 3

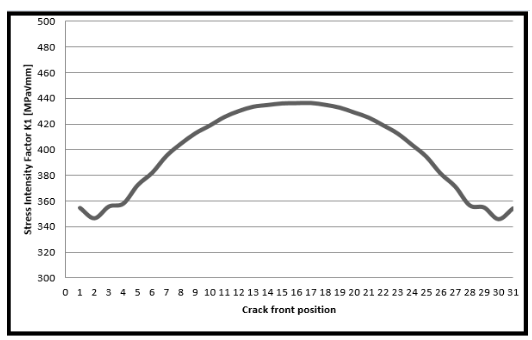

Figure 3. SIF KI vs. crack front position

The stress intensity factor solution for this problem is given by M. Vorel and E. Leidich [4] as shown in the figure 4.

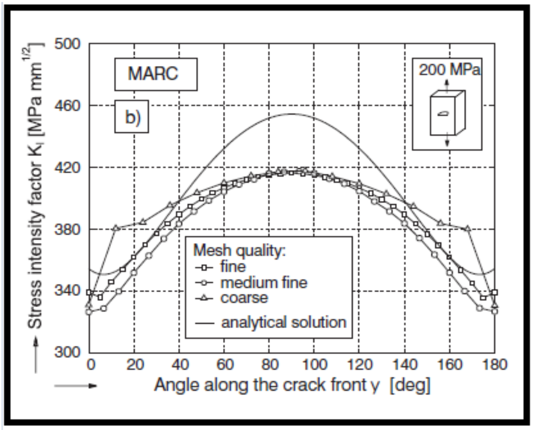

Figure 4. SIF K vs. angle along the crack front

The results obtained from the literature and also of the analysis conducted on the ANSYS software are a close match. This establishes the credibility of the software, and thus it can be employed for testing a drive shaft under Mixed-Mode fracture.

4. Loading And Boundary Condition

Another important input to the analysis is the application of boundary condition. In reality the shaft is subjected to repeated torsion loading. From calculation the maximum torque was 612 N-m. This torque was then applied at one end of the shaft while all the displacements at other end was fixed.

Static analysis was conducted to find out the critical region on the drive shaft. The figure 5 given below shows the maximum stress region.

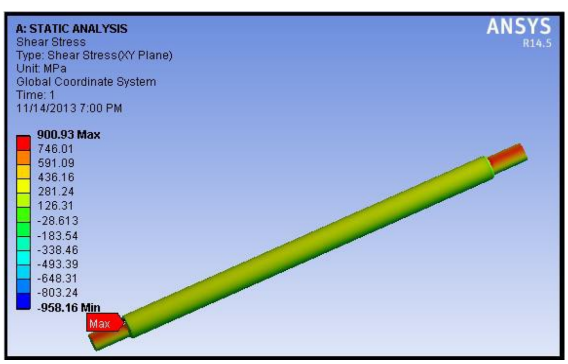

Figure 5. Maximum shear stress at fillet region

5. Finite Element Model

Finite element modelling is defined here as the analyst's choice of material models, finite elements (type/shape/order), meshes, constraint equations, pre and post processing options, governing matrix equations and their solution methods available in a chosen commercial FEA program for the intended analysis. The proposed finite element model involves a fine mesh of singular isoparametric pentahedral solid elements (SPENTA15) with user specified number NS and length Δa from one crack face to another and number of segments (NSEG) along the surface crack front.

A compatible mesh of regular elements (NREG) namely isoparametric pentahedral solid element (PENTA15) and isoparametric hexahedral solid element (HEXA20) are used to discretize the rest of the domain. While introducing the crack, the most important region is the region around the edge of the crack. This edge of the crack known as crack front should be modelled in such a way that it can simulate stress singularity. The edge of the crack referred as crack front in a 3D model is shown in the figure 6.

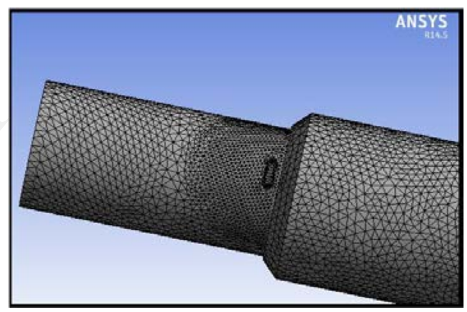

Figure 6. Meshed model

To pick up singularity in the strain, the crack front should be co incident, and the elements around the crack tip should be quadratic with mid side nodes placed at the quarter point. Such elements are called singular elements.

6. Stress Intensity Factor

The fracture tool is used to calculate the stress intensity factor KI, KII and KIII, the following steps are followed

1. Define a local crack front with X-axis parallel to crack face and Y-axis perpendicular to crack face
2. Define crack front divisions, mesh contours and length of crack
3. Obtain KI, KII and KIII

7. Results

Various iterations were carried out for different crack lengths and depths and it was found that for a crack length of 5.72mm and depth of 2.288mm, the stress intensity factor KII was equal to the fracture toughness of material as shown in the figure 7.

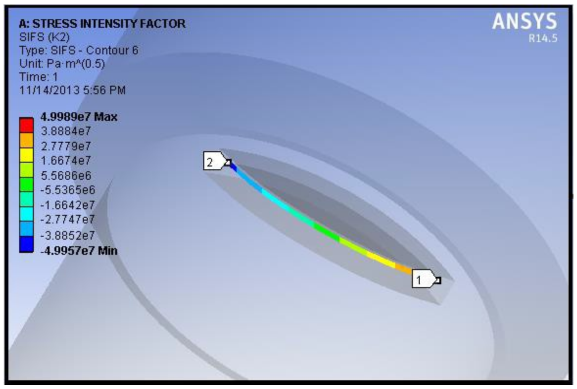

Figure 7. Profile of the critical crack

SIF was evaluated for different crack lengths. The plot below shows the stress intensity factor for mode 1, mode 2 and mode 3 for a critical crack length of 5.72mm and depth of 2.288mm along the crack front position.

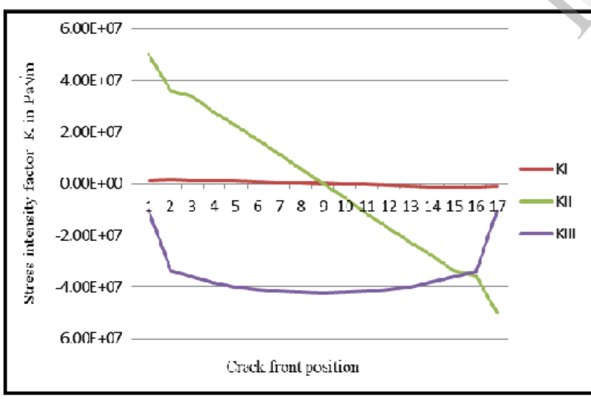

Figure 8. Variation of SIF along crack front position

Using paris equation, the crack growth rate and number of fatigue cycles to failure was calculated which is tabulated.

Table 2. Fatigue crack growth rate and total number of cycles for different crack lengths

Crack length 'a' in mm	Fatigue crack growth rate in m/cycle (da/dN)	Total number of cycles in millions (N)
0.8	8.825E-8	9.065
1.6	7.854E-7	10.084
2.4	1.676E-6	10.561
3.2	3.1653E-6	10.814
4	4.03E-6	11.081
4.8	5.107E-6	11.169
5.6	6.361E-6	11.815
5.72	6.8E-6	11.199

The plot shown below gives the variation of fatigue crack growth rate with crack length

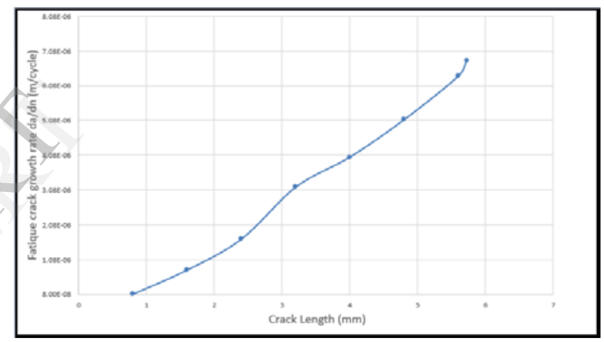

Figure 9. Fatigue crack growth rate vs. crack length

8. Conclusion

1. Static stress analysis for the operating conditions on drive shaft was performed. Crack zone in the drive shaft was identified near the fillet region of shaft, maximum principal stress of 900MPa occurred in this region.
2. The stress intensity factor (SIF) is found to have the maximum value at the edges along the crack front.
3. It is found that the failure of the shaft occur due to mode II crack propagation, the value varies from 11.8MPa√m to 49.99 MPa√m
4. Referring to the results obtained in the figure 9, fatigue crack growth rate at the surface increases with increasing in crack length
5. For some crack lengths SIF KII becomes negative. It indicates that the crack length is subjected to closing mode or compression

which was considered that increases the fatigue life cycles to failure.

9. References

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