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Simulating Fatigue Propagation Life of Martensitic Steel

[1]O.O. Ajayi and [2]J. Ikotun
[1]Department of Mechanical Engineering,
[2]Department of Civil Engineering, Covenant University, P.M.B. 1023, Ota, Nigeria

Abstract: The linear elastic fracture mechanics equation together with that for stress intensity factor range ΔK, was used to develop a fatigue propagation life model, after substituting parameters of material constants. The model was then employed in creating simulation software which can be used at any time to generate data, make design consideration and predict response to variable loading. This became useful in predicting the life of metal from the point of crack initiation; investigate behaviour to changes in crack sizes and also determine adequate damage tolerance for the metal.

Key words: Fatigue life, crack development, modelling, metal, fracture

INTRODUCTION

Fracture is the fragmentation of a solid into two or more parts under the action of stress (Dieter, 1988). Its process can be considered to be made up of crack initiation and growth and can be classified into two broad headings namely ductile and brittle fracture. While ductile fracture is characterized by appreciable amount of plastic deformation prior to and during the propagation of crack, with an amount of gross deformation present at the crack surface, brittle fracture is characterized by a rapid rate of crack propagation, without gross deformation but little micro deformation (Dieter, 1988; Shaffer *et al*., 1999). It occurs in engineering structures and can be costly in terms of human and/ or property damage (Benham *et al*., 1996; Odukwe *et al*., 2007).

Many researchers have reviewed some structural damages, beginning from the late 1800s (Dieter, 1988; Benham *et al*., 1996; Odukwe *et al*., 2007), when members of the British Iron and Steel Institute reported the mysterious cracking of steel in a brittle manner. Investigation shows that the most failures were initiated in welds that are defective. Later discoveries also reveal that crack initiation and growth in structures resulted in sudden failures (Anderson, 1995). However, in spite of design improvements, increased use of crack arresters, use of quality materials and so on, brittle fractures still occurs in ships within the 1950s. This occurrence continued up to 1988 when the fuselage of a 19 year old Boeing 737 airline ripped open in flight (Chau and Chan, 2002). The cause was found to be due to fatigue crack propagation from a rivet hole in the fuselage of the jet. In real sense, most cracks nucleate in areas of increased stress concentration and propagate unnoticed within the microstructure of the material (Courtney, 2000; Dieter, 2000). Fracture mechanics have shown that because of the interrelations among materials, design, fabrication and loading, fatigue failure cannot be eliminated merely by using materials with improved notch toughness (Tomkins *et al*., 1981; Anderson, 1995; Miller and Akid, 1996). The failures still occurs today. Moreover, materials subjected to fluctuating stresses can fail at stresses much lower than their yield stress (Odukwe *et al*., 2007).

Reliability studies had shown that structural members contain pre-existing cracks which may have resulted during fabrication (Tomkins *et al*., 1981; Dieter, 1988, 2000; Odukwe *et al*., 2007). These cracks are assumed to be known and therefore, efforts are geared towards determining the remaining

Corresponding Author: O.O. Ajayi, Department of Mechanical Engineering, Covenant University, P.M.B. 1023, Ota, Nigeria Tel: +234-8036208899

number of cycle of loading to failure (Dieter, 2000). The number of these cycles from the point of crack initiation to failure is the fatigue propagation life of the material, which depends on when and how a crack initiates and the rate at which it grows through the microstructure (Tomkins *et al*., 1981). Most fatigue failure have been discovered to be caused by cracks, which initiates unnoticed and grows at a fast rate through the structural member, it is easily the most common type of failure of engineering structures in service and difficult to foresee, because conditions causing it are frequently not easily recognizable (Sobczyk, 1987; Odukwe *et al*., 2007).

More over, advances in fatigue design had shown that relationship exist between the rate of crack growth da/dN and the stress intensity factor range ΔK, obtained by plotting a log-log graph of da/dN on the ordinate against ΔK on the abscissa. The resulting plot is a sigmoid curve which can be divided into regions I-III (Dieter, 1988, 2000; Courtney, 2000; Ashby and Jones, 2005). Region I is called the non-propagating crack region, II is the linear elastic fracture mechanics range and III is the accelerated crack growth region that is followed by failure respectively. The region II is represented by the power law as (Benham *et al*., 1996; Courtney, 2000):

$$\frac{da}{dN} = A(\Delta K)^{M} \tag{1}$$

where, A, M are material constants determined by experimental procedures.

Further study on Eq. 1 was carried out by Odukwe *et al*. (2007), which analyzed experimental conclusion on high yield strength (σ_y = 100 Ksi (689 MN m^{-2}), critical stress intensity factor (K_c) = 150 Ksi $[in]^{1/2}$ (165 MN mm^{-2})) Martensitic steel in air environment. It was discovered that ΔK explains about 99.85% of the changes in da/dN and that as a result of experimental analysis $A = 7.244\times10^{-9}$ and M = 2.22 for Martensitic steel. When crack growth and stress intensity factor are correlated, it is possible to use data generated under constant amplitude loading to determine the fatigue life of a component (Dieter, 2000; Odukwe *et al*., 2007). The knowledge of when a material will fail and the required number of cycles to failure will aid in knowing the rate of changeability and maintenance of such material, therefore, researchers must look into the problem of structural failures with a view to bring ideas and develop new packages, which can be used to generate data and evolve new design considerations, so that the problem of catastrophic failure will be a forgone issue. This can be achieved by developing interactive software which can be used on the field and at any time to determine design consideration and loading parameters. This research focused on achieving this, by using Eq. 1 together with the stress intensity factor range to develop a simple model and therefore carry-out the simulation process for Martensitic steel. It is also sort to extend such simulation to include other metals.

MATERIALS AND METHODS

The linear elastic fracture mechanics equation, represented by Eq. 1 was employed with the relation for ΔK presented as Eq. 2. Constant amplitude stresses, σ of 15 Ksi (103.43 MPa), 20 Ksi (137.90 MPa) and 25 Ksi (172.38 MPa), together with values of material constants A and M developed by Odukwe *et al*. (2007) were used to develop a possible fatigue life model of Martensitic steel containing edge and surface cracks as follows:

$$\Delta K = C\sigma^{M}\sqrt{(\pi a)} \tag{2}$$

Where:
C = Constant for edge and surface cracks = 1.12 (Odukwe *et al*., 2007)
a = Average crack size

Putting (2) into (1) gives:

$$\frac{da}{dN} = AC^M \sigma^M \pi^{M/2} a^{M/2} \tag{3}$$

Integrating from N_o to N_f gives:

$$N_f = \frac{1}{\left(AC^M \sigma^M \pi^{M/2}\right)} \int \frac{da}{a^{M/2}} + N_o \tag{4}$$

Substituting values of A, M and C given earlier gives:

$$N_f = \frac{273820527.20}{\sigma^M}\left(a_o^{-0.11} - a_f^{-0.11}\right) + N_o \tag{5}$$

The Eq. 5 above is therefore the constant amplitude fatigue life model of Martensitic steel containing edge and surface crack. This is employed to develop a simulation that can be used at any time to generate data for design consideration, change and modify design parameter, predict and determine safe operating conditions or damage tolerance for the metal. The simulation is Fig. 1.

where, A = Are you working on Martensitic steel? And B = Do you have more data?

RESULTS AND DISCUSSION

Simulation Result

The result of the number of cycles corresponding to the crack sizes from 0.2 inches (5.08 mm) and above is shown in Table 1. This is obtained from the simulation software after the desired crack sizes are inputted.

Table 1 show that a pre-existing crack size of 0.2 inches (5.08 mm) was assumed present. Crack sizes were pre-suggested and the corresponding numbers of crack propagation cycles were then

Table 1: The number of cycles of loading corresponding to desired crack sizes, obtained from simulation software

Desired crack sizes (inches) ×25.4 mm	No. of cycles (cycles), when σ = 15 Ksi (103.43 MPa)	No. of cycles (cycles), when σ = 20 Ksi (137.90 MPa)	No. of cycles (cycles), when σ = 25 Ksi (172.38 MPa)
0.20			
0.35	47798.50	25237.73	15378.36
0.40	58775.56	31033.65	18910.05
0.55	84312.65	44517.29	27126.17
0.62	93690.41	49468.77	30143.31
0.79	112284.52	59286.51	36125.65
0.87	119549.65	63122.52	38463.08
0.98	128411.25	67801.46	41314.15
1.52	160095.10	84530.615	51507.90
1.70	167932.32	88668.69	54029.39
1.92	176345.55	93110.90	56736.20
2.20	185624.23	98010.06	59721.46
2.35	190070.15	100357.52	61151.86
2.45	192862.54	101831.91	62050.27
2.60	196822.28	103922.66	63324.25
2.85	202889.30	107126.07	65276.21
3.00	206252.41	108901.79	66358.23
3.35	213423.48	112688.14	68665.40
3.48	215877.50	113983.87	69454.94
3.65	218937.31	115599.46	70439.39
3.95	223969.56	118256.50	72058.43

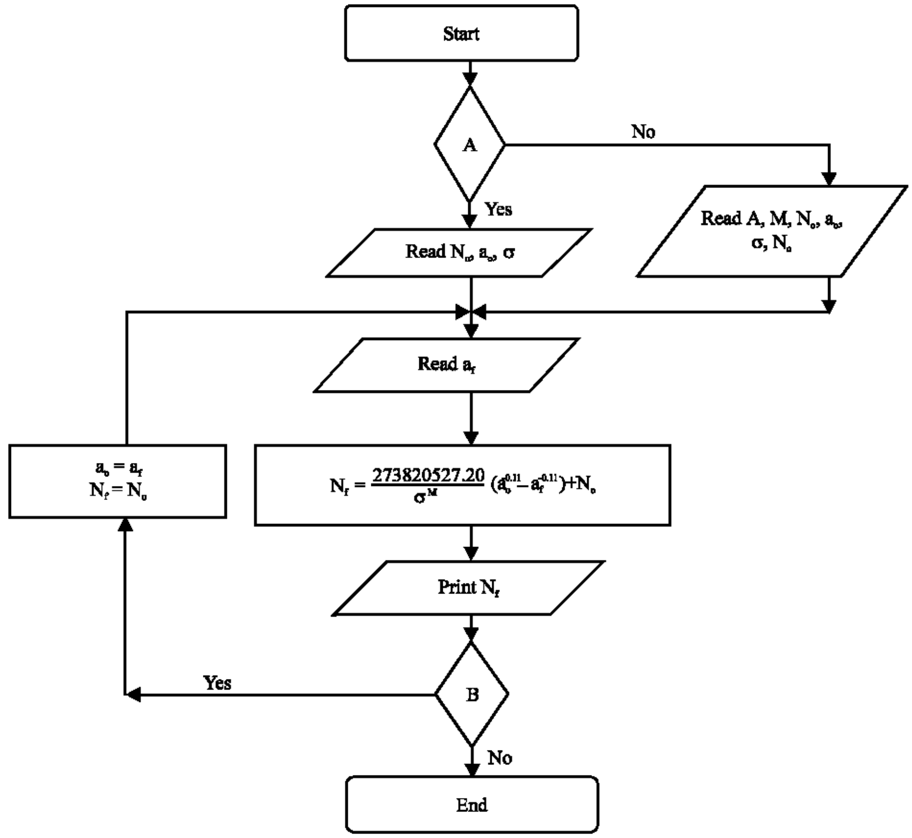

Fig. 1: Simulation flowchart representing fatigue propagation life of Martensitic Steel, extended to include other metals

determined by employing the software developed from the simulation (Fig. 1). The plot of Fig. 2 reveals that the constant amplitude stress is inversely related to the number of cycles but directly to the crack size. This is expected because, as the stress builds up, the energy release rate required to propagate the crack on a pre-cracked surface increases and thus, crack increment occurs when the increase in the energy release rate is at least equal to the energy required to create a new crack surface (Dieter, 1988; Anderson, 1995; Miller and Akid, 1996), thereby, lowering the number of crack propagation cycles required to create the new crack length. Thus, inferring that, as the constant amplitude stress increases, the required surface energy of the cracked surface increases, the material resistance to crack extension reduces and thus, crack growth takes place with reduced number of cycles of loading (Pascual and Meeker, 1999). The findings of many researchers (Benham *et al*., 1996; Felbeck and Atkins, 1996; Shaffer *et al*., 1999; Courtney, 2000; Dieter, 2000; Shigley *et al*., 2004; Smith and Hashemi, 2004) further support this. More so, at a constant amplitude stress value, the number of cycles increases with increasing crack lengths. This is the basis for the linear elastic fracture mechanics which relates the rate of crack growth to the average crack length at constant amplitude stress (Benham *et al*., 1996; Courtney, 2000). In addition, Fig. 2 reveals the following: that, at constant crack size, the number of cycles decreases with increasing stress values and also that, at constant number of cycles, crack sizes increases with increasing stresses. These information can be used adequately in mechanical reliability design of machine parts, where the designer may wish to know the

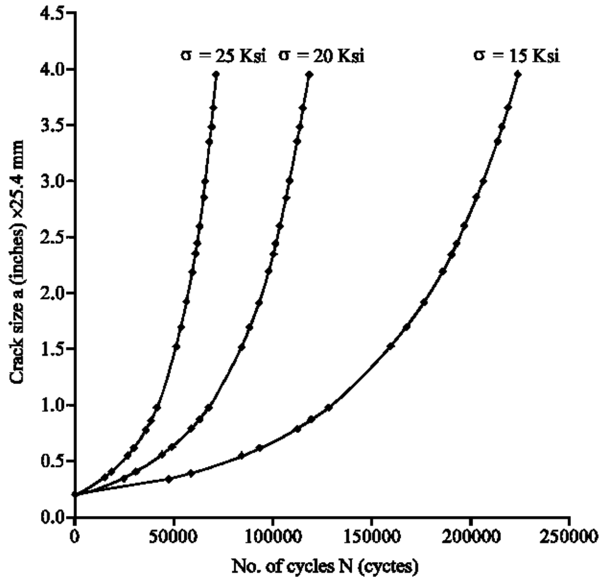

Fig. 2: Plot of desired crack sizes against corresponding number of crack propagation cycles, determined from the simulation software

behaviour of such part under different loading conditions, when it is desired that crack size or number of cycles are to be kept constant. This would aid in gaining quick access to valid information and also determine safe operating conditions. Moreover, the use of the simulation software, if employed in design, will create flexibility, as design parameters can be changed at ease and corresponding predictive response can easily be determined without recourse to rigorous and expensive experimentation.

CONCLUSION

The simulation of the fatigue propagation life of Martensitic steel has been done. A model developed from the linear elastic fracture mechanics equation together with the relation for the stress intensity factor range was employed in the modeling and simulation work. The resulting simulation software was then used to investigate the behaviour of the metal to different constant amplitude loading stresses and found to be adequate, as result obtained agreed with previous findings. This became useful in predicting the life of the metal from the point of crack initiation and to investigate its behaviour to changes in crack sizes and also determine adequate damage tolerance for the metal. Thus, removing the cumbersome computational and repetitive processes involved in data generation and adds pleasantness and speed to design.

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