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Simulation of Crack Growth Rate in Martensitic Steel

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Abstract: This research used the stress intensity factor with rate of crack growth per cycle of loading to model and simulates the crack growth in Martensitic steel in air environment. The basic parameters used were da/dN and ΔK, log (da/dN) was analyzed against log (ΔK) and a regression analysis using data from log (da/dN) vs log (ΔK) was carried out and the outcome employed to develop a model and simulation which gave rise to interactive software that can be used to predict the behavior of a structural member under conditions of certain loading. Additionally, it can be employed to have quick access to data and design considerations, when input data are supplied. This became useful in monitoring the point at which crack can initiate and the rate at which it would grow in a particular structural member of interest. The software has been tested with theoretical and experimental data.

Key words: Fatigue, regression analysis, model, simulation

INTRODUCTION

Crack is the alternative opening and closing of regions, which begins from a notch hole. It initiates unnoticed and grow at a very fast speed through structural members, also, it has been found to be a major cause of most fatigue failures (Budynas, 1998; Shaffer *et al*., 1999; Henkel and Pense, 2001). Fatigue is the process by which a material fractures when subjected to cyclic stresses below the maximum static strength of the material, and could be of high and low strain (Broek, 1985; Anderson, 1995; Budynas, 1998; Henkel and Pense, 2001; Hugh and Spalding, 2004). It occurs unnoticed within the microstructure of a material normally at a point of stress concentration and lead to catastrophic results if allowed to develop further than the material can withstand. The extent to which this crack grows depends on the brittleness of the material (Anderson, 1995; Budynas, 1998; Henkel and Pense, 2001). Brittle fractures are prevalent in engineering structures, and could be costly in terms of human life and/or property damage (Anderson, 1995).

Many researchers have reviewed the structural failures beginning in the late 1800s and also profile the catastrophic effects of the failures (Broek, 1985; Anderson, 1995; Budynas, 1998; Henkel and Pense, 2001). The primary causes of these failures were established to be unusually high loading stress; poor details and fabrication which result in cracks; the growth of a flaw to a critical size; stress-corrosion cracking; different levels of temperatures; expansive disruption by physical or chemical means; rotation; expansive distortion to mention but a few (Broek, 1985; Anderson, 1999; Fisher and Alan, 2000; Beer *et al*., 2001). However, fracture mechanics have shown that because of all the interrelations among materials, design, fabrication, and loading, brittle fractures cannot be eliminated in structures merely by using materials with improved notch toughness (Roylance, 1995; Henkel and Pense, 2001). It is essential to know the range of parameters which will be allowable for structures before designers carry out structural designs. This involves knowing the right design considerations necessary. 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. The prior knowledge of when a material can fail will aid in knowing the rate of changeability and maintenance of such materials. Based on this, the authors at the University of Nigeria, Nsukka, Nigeria, between 2003 and 2004, carried out this work which is aimed at creating simple model to simulate the crack growth rate and its initiation, using martensitic steel which is high alloy steel and a perfect example of the particulate composites (Henkel and Pense, 2001). Thereby, developing interactive software, that can be used at any time to predict the behaviour of a structural member under conditions of certain loading. It will also be useful in knowing when crack can initiate and the rate at which it would grow in a particular structural member of interest.

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Fatigue-crack growth rates can be determined from a wide range of specimens including those used for fracture toughness testing; however different procedures are available for different tests (Shaffer *et al.*, 1999; Smith, 2004). The widely accepted involves using a constant amplitudes loading stress. The measurements of crack length (by optical method) (Anderson, 1995; Shaffer *et al.*, 1999) and number of cycles at intervals of crack growth per cycle of loading (Smith, 1981, 2004) are taken and recorded. These are used to calculate values of the changes in the stress intensity factor ΔK and the rate of crack growth per cycle of loading da/dN for various crack lengths. Data from one or more specimens are then used to determine the relationship between ΔK and da/dN, either by direct calculations between successive pairs of reading or graphically by plotting a graph of crack length against number of cycles of loading. There is always a scatter existing in the data collected due to the type of testing method used. A better approach involves plotting a graph of da/dN against ΔK (Anderson, 1995; Shaffer *et al.*, 1999). In this, the amount of scatter that exists is very minimal, and a straight line through almost all the data can be drawn. The nature of the log-log plot between da/dN against ΔK is a sigmoid curve, which gives room for assumptions and cut-offs. To avoid this, a method of approach is to convert this curve to a straight line approximation, so that, the simulation of the model equation would lead to the generation of data at any required point. This can be achieved using a linear regression analysis. For the purpose of this study, experimental conclusion published in (Barsom and Rolfe, 1969) for A514 martensitic steel in air was analyzed and the computation of log (da/dN) and log (ΔK) was carried out. The values of log (da/dN) are then plotted and also regressed against that of log (ΔK). The output summary of the outcome was then employed.

MATERIALS AND METHODS

The result of an experiment conducted on a high yield strength (σ_y = 100 Ksi (or 689 MN m^{-2}), critical stress intensity factor (K_c) = 150 Ksi $[in]^{1/2}$ (165 MN mm^{-2}) martensitic steel in air environment from a flaw size ranging from 0.30 and above presented in (Barsom and Rolfe, 1969) and a stress change (Δσ) of 20 Ksi (138 MN m^{-2}) was used to generate data for this study. Table 1 below gives data of flaw size ranging from 0.3 to 1.57 in (7.6 to 39.9 mm).

Where $\Delta K = C\ \Delta\sigma\ [\pi a_{av}]^{1/2} = 39.70[a_{av}]^{1/2}$ (Anderson, 1995; Budynas, 1998),

C = 1.12 for edge and surface cracks (Anderson, 1995)

Table 1: Values of changes in stress intensity factor ΔK and crack growth per cycles of loading (da/dN) corresponding to the measured crack lengths (a)

No.		a (in)	ΔK (Ksi √ in)	da/dN (in/cycle)
0	=	0.30		
1		0.39	23.32	7.89×10^{-6}
2		0.41	25.10	9.31×10^{-6}
3		0.49	26.63	1.06×10^{-5}
4		0.57	28.90	1.28×10^{-5}
5		0.62	30.62	1.46×10^{-5}
6		0.70	32.25	1.64×10^{-5}
7		0.74	33.69	1.81×10^{-5}
8		0.80	34.84	1.95×10^{-5}
9		0.88	36.39	2.15×10^{-5}
10		0.95	37.93	2.36×10^{-5}
11		1.00	39.20	2.54×10^{-5}
12		1.07	40.38	2.71×10^{-5}
13		1.15	41.83	2.94×10^{-5}
14		1.19	42.94	3.12×10^{-5}
15		1.24	43.76	3.25×10^{-5}
16		1.30	44.74	3.42×10^{-5}
17		1.35	45.70	3.58×10^{-5}
18		1.39	46.47	3.72×10^{-5}
19		1.48	47.56	3.84×10^{-5}
20		1.57	49.03	3.97×10^{-5}

Taking the log values of column 2 and 3 of Table 1 gives Table 2 and the result of regression analysis of data in Table 2 is summarized in Table 3

Table 2: Values of log ΔK and log da/dN of columns 2 and 3 in Table 1

Log ΔK (ksi (in)$^{1/2}$	Log da/dN (in/cycle)
1.37	- 5.10
1.40	- 5.03
1.43	- 4.97
1.46	- 4.89
1.49	- 4.84
1.51	- 4.79
1.53	- 4.74
1.54	- 4.71
1.56	- 4.67
1.58	- 4.63
1.59	- 4.60
1.61	- 4.57
1.62	- 4.53
1.63	- 4.51
1.64	- 4.49
1.65	- 4.47
1.66	- 4.45
1.67	- 4.43
1.68	- 4.42
1.69	- 4.40

RESULTS AND DISCUSSION

Comparing results from Table 3 with Fig. 2, shows that, that from the former is more accurate than the latter. This is as a result of approximations which arise from scale factor. Thus, from Table 3, the slope and intercept are 2.22 and 8.14, respectively. However, the measure of the explanatory power of the model (R^2) obtained is suggestive of the fact that stress intensity factor (ΔK) is directly responsible for 99.85% of changes in rate of crack growth per cycle (da/dN). More so, a linear estimation can be deduced as:

$$\text{Log (da/dN)} = 2.22 \log (\Delta K) - 8.14 \qquad (1)$$

Testing the statistical significance of the estimated coefficients: The linear estimation is Eq. 1.

Rule: if S_{bi}<bi/2 then, bi is statistically significant and different from zero. Meaning that bi is a significant variable in explaining the change in the dependent variable. Where S_{bi} is the standard errors and bi is the coefficients (Nyong, 1998). Thus from Table 3, the slope is statistically significant and not zero. Therefore, log ΔK is a significant causal variable in explaining changes in log (da/dN), not the intercept. This is a justification of the PARIS equation (Henkel and Pense, 2001), given by Eq. 2.

$$da/dN = A\,(\Delta K)^{M} \quad (2)$$

Thus, a re-model of Eq. 2 is Eq. 1. The latter being a linear form of the former. This model has been employed in this simulation work. The flowchart that resulted is presented in Fig. 3. This led to the development of general software using Visual Basic Programming language to incorporate other metals, once their A, m and ΔK are known, it can generate the rate of crack growth and other parameters like change in crack length, final or initial crack length, and also final or initial number of cycles. If it is to be used to predict initiation point then, the critical stress intensity factor must be inputted and if it is to be used for martensitic steel , 7.24×10^{-9} should be substituted for A and 2.22 for m.

Table 3: The results of regression analysis of log ΔK against log da/dN from Table 2

Regression statistics	
Multiple R	0.999229532
R square	0.998459659
Adjusted R square	0.99836905
Standard error	0.007820403
Slope	2.220673188
Standard error on slope	0.021154532
Intercept	-8.138260803
Standard error on intercept	0.033383335
Observations	19

Plotting the graph of da/dN against ΔK gives the sigmoid curve of Fig. 1, while that of log (da/dN) against log (ΔK) gives (Fig. 2)

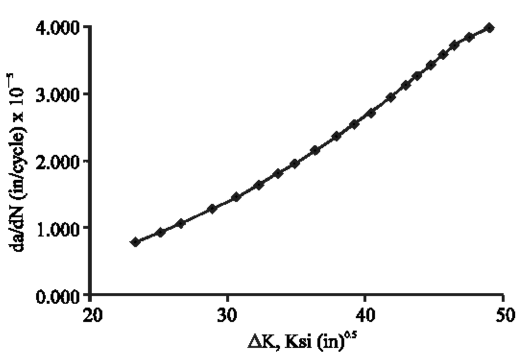

Fig. 1: The sigmoid curve resulting from a direct plot of Crack Growth Per cycle of Loading (da/dN) against Changes in Stress Intensity Factor (ΔK)

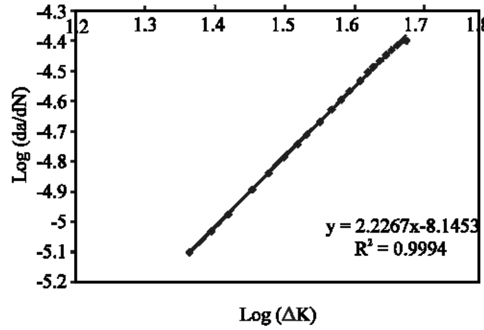

Fig. 2: Plot of log (da/dN) against log (ΔK)

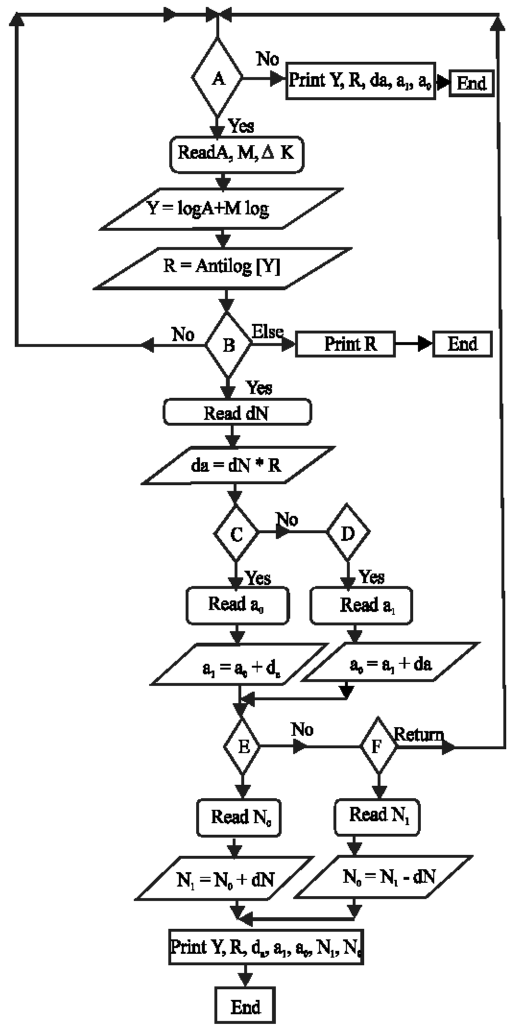

Fig. 3: Flowchart of simulation of Crack initiation and growth Where A = determine crack growth rate?, B = determine change in crack length ?, C = determine final crack length?, D = determine initial crack length?, E = determine final No. of cycles? And F = determine initial No. of cycles?

CONCLUSION

The simulation of crack growth in martensitic steel has been done. A remodel of the Paris equation developed in the study was employed. The value of the slope agrees with Pook (1979). This has removed the cumbersome computational and repetitive processes involved in data generation and adds pleasantness and speed to design. More so, the numerous assumptions involved with the analysis using the sigmoid curve has been eliminated and the crack growth rate, the number of cycles, crack initiation point, final crack length, and even point of failure of a cracked member can be predicted by merely using the simulation and/ or software developed, once the desired ΔK, A, m and change in number of cycle are inputted. The simulation software has been tested with various theoretical and experimental data and found to be adequate.

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