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Influence of node release in crack propagation simulation under variable amplitude loading

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Abstract

The aim of this paper is to verify the effect of different crack propagation rates in determination of crack opening and closing stress of an ASTM specimen under a standard suspension spectrum loading from FD&E SAE Load Histories by finite element analysis. The crack propagation simulation was based on nodes release in the minimum loads to minimize convergence problems. To understand the crack propagation processes under variable amplitude loading, retardation effects are observed and discussed.

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Keywords: Fatigue, crack propagation simulation, finite Element method, retardation

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1. Introduction

The most common technique for predicting the fatigue life of automotive, aircraft and wind turbine structures is Miner's rule (1945). Despite the known deviations, inaccuracies and proven conservatism of Miner's cumulative damage law, it is even nowadays being used in the design of many advanced structures. Fracture mechanics techniques for fatigue life predictions remain as a backup in design procedures. The most important and difficult problem in using fracture mechanics concepts in design seems to be the use of crack growth data to predict fatigue life. The experimentally obtained data is used to derive a relationship between stress intensity range (ΔK) and crack growth per cycle (da/dN).

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In cases of fatigue loaded parts containing a flaw under constant stress amplitude fatigue, the crack growth can be calculated by simply integrating the relation between da/dN and ΔK. However, for complex spectrum loadings, simple addition of the crack growth occurring in each portion of the loading sequence produces results that very often are more erroneous than the results obtained using Miner's rule with an *S-N* curve. Retardation tends to cause conservative Miner's rule life predictions where the fatigue life is dominated by the crack growth. However, the opposite effect generally occurs where the fatigue life is dominated by the initiation and growth of small cracks. In these cases, large cyclic strains, which might occur locally at stress raisers due to overload, may pre-damage the material and lower its resistance to fatigue. This effect is generally handled by basing the crack initiation life prediction on a modified (lowered) strain-life or stress-life curve that includes the effect. In Schijve (1960) observed that experimentally derived crack growth equations were independent of the loading sequence and depended only on the stress intensity range and number of cycles for a given portion of loading sequence. The central problem in the successful utilization of fracture mechanics techniques applied in a fatigue spectrum is to obtain a clear understanding of the influence of loading sequences on fatigue crack growth. Of particular interest in the study of crack growth under variable amplitude loading is the decrease in the growth rate called crack growth retardation that usually follows a high overload. Most of the reported theoretical descriptions of retardation are based on data fitting techniques, which tend to hide the behavior of the phenomenon. If the retarding effect of a peak overload on the crack growth is neglected, the prediction of the material lifetime is usually very conservative, Ditleveson and Sobczyk (1986). The small scale yield model employs the Dugdale (1960) theory of crack tip plasticity, modified to leave a wedge of plastically stretched material on fatigue crack surfaces. Fatigue crack growth was simulated by Skorupa and Skorupa (2005) using the strip model over a distance corresponding to the fatigue crack growth increment as shown in Fig. 1.

Nomenclature

K_{max}	maximum stress intensity factor
P_{min}	minimum applied load
P_{max}	maximum applied load
B	specimen thickness
a	crack length
W	width of the specimen
a/W	ratio of the crack length to the specimen width
$f(a/W)$	characteristic function of the specimen geometry
r_y	cyclic plastic zone size
σ_y	effective yield strength.

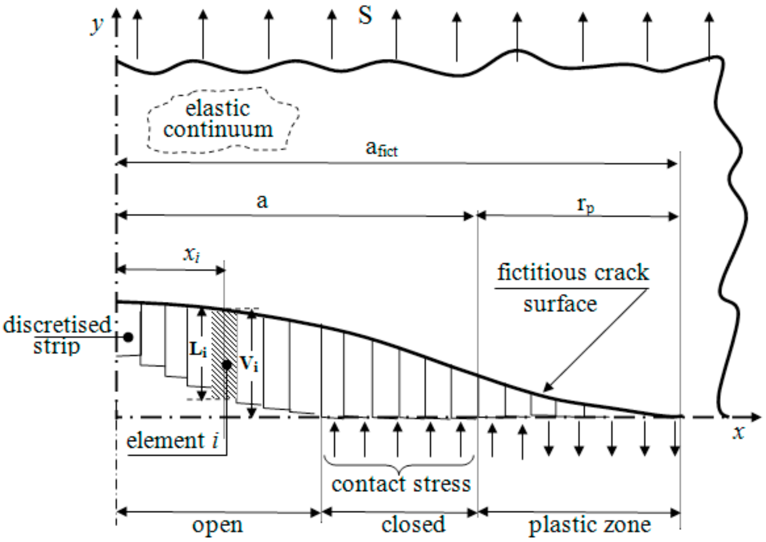

Fig. 1 Schematic Small Scale Yield Model (Newman (1975))

In order to satisfy the compatibility between the elastic plate and the plastically deformed strip material, tensile stress must be applied on the fictitious crack surfaces. Tensile stresses are also needed over some distance ahead of the crack tip in the crack wake region as shown in Figure 1 ($a_{open} \le x < a$), where a_{open} indicates the crack opening, where the plastic elongations of the strip *L(x)* exceed the fictitious crack opening displacements, *V(x)*, and in the plastic zone ($a \le x < a_{fict}$),where a_{fict} indicates a fictitious crack extension as in the original Dugdale model. In the real world of application like automotive, aeronautic, naval and wind turbine for example, the loading history is random and it is to necessary edit the signal in a way so the edition does not affect the quality of results when used for numerical and experimental activities. Genesis (2001) is a fatigue code used to generate the standards spectrum loadings for some of the mentioned application like Aircher (1976) with FALSTAFF for aeronautics and WISPER for wind turbine. These spectrum loadings will be the first input for the engineers perform the numerical and experimental models. In literature it is very hard to find works regarding the procedure to determine the when crack opening or closing due to random loading cycle by cycle; normally is used by blocks of cycles with the same amplitude. In this work will be presented a crack propagation model with five different crack advance rates and the results and effects in a compact tension specimen (CT) under variable amplitude loading.

2. Description of model

A compact tension specimen was modeled using a commercial finite element code, MSC/Patran, r1 (2008) and ABAQUS Version 68 (2002) used as solver. Half of the specimen was modeled and symmetry conditions applied. A plane stress constraint is modeled by finite element method covering the effects in two dimensional (2D) small scale yielding models of fatigue crack growth. The boundary conditions are presented in Fig. 2. The finite element model has triangle elements, S8, with quadratic formulation and spring elements, SPRING1.

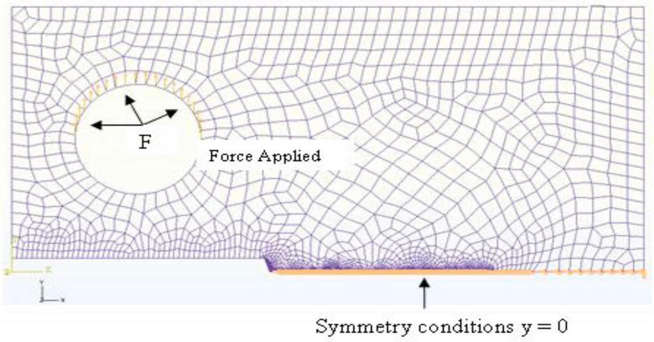

Fig. 2 Half Compact Tension Modeled by FEM

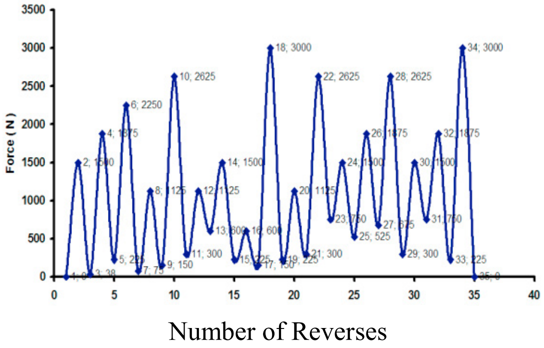

Fig. 3 FD&E SAE Suspension Modified Load

To compute K_{max} equation (1) is used. The value of K_{max} is computed as 0.6 K_{IC} where K_{IC} is the critical stress intensity factor of material. K_{max} will be used to compute the cyclic plastic zone size by the Irwin equation (2).Fatigue crack growth is simulated by node releasing at crack tip, P_{min}, followed by a single loading cycle $P_{min} \rightarrow P_{max} \rightarrow P_{min}$, Fig. 3. The force is divided into steps of loads P_{min}- P_{max} and nine steps of unloads P_{max}-P_{min}, in each cycle. The smaller element 0.025 mm, was estimated based on the cyclic plastic zone size ahead of the crack tip and computed by (2). Will be used only 10 cycles from load history to identify crack opening/ closing and retardation effects.

$$K_{max} = \frac{P_{max}}{BW^{1/2}} f\left(\frac{a}{W}\right) \tag{1}$$

$$r_y = \frac{1}{8\pi}\left(\frac{K_{max}}{\sigma_y}\right)^2 \tag{2}$$

Where: $\boldsymbol{K_{max}}$ = maximum stress intensity factor; $\boldsymbol{P_{min}}$ = minimum applied load; $\boldsymbol{P_{max}}$= maximum applied load; $\boldsymbol{B}$ = specimen thickness; $\boldsymbol{a}$ = crack length;$\boldsymbol{W}$ = width of the specimen; $\boldsymbol{a/W}$ = ratio of the crack length to the specimen width; $\boldsymbol{f(a/W)}$ = characteristic function of the specimen geometry; $\boldsymbol{r_y}$= cyclic plastic zone size;$\boldsymbol{\sigma_y}$ = effective yield strength. To evaluate the crack propagation, a nonlinear analysis is used to compute the deformation history, cycle by cycle, using the Newton-Rapson method. The procedure to estimate where the crack is opened or closed is based on the work of Wei & James (2000). These authors considered that the crack closure occurs at the first contact behind the crack tip; a second criterion is that the surface at the crack tip must be in compression. This can be observed when the displacements of nodes in the crack tip area are negatives in (y) direction. Material properties: $\sigma_{YS=}$ 230 MPa; $\sigma_{TS=}$ 410 MPa; E= 210GPa; e=0,21; υ=0,3.

The dimensions of the compact tension specimen were: B=3.8 mm; W= 50.0 mm; a/W= 0.26. Table 3 shows the estimated and used values of the cyclic plastic zone sizes as well as smaller finite element. The smaller element size 0.025 mm was estimated based on the cyclic plastic zone size ahead of the crack tip and computed by the Irwin equation (2). The values used in Table 3 have been chosen with intention to improve the quality of results when will be compared with experimental results. Table 4 shows the difference crack propagation rates used in the current work.

Table 3 Smaller Finite Element Size

	Cyclic Plastic Zone Size	Smaller Finite Element Size
	(mm)	(mm)
Estimated	0.48	0.048
Used	0.10	0.025

Table 4 Crack Propagation Rate

Model	Crack Propagation Model
	(mm/cycle)
1	0.25
2	0.5
3	0.75
4	1.0

3. Results

Figures 4 and 5 present respectively crack opening stress, σ_{op} and crack closing stress, σ_{cl} against numbers of cycles.

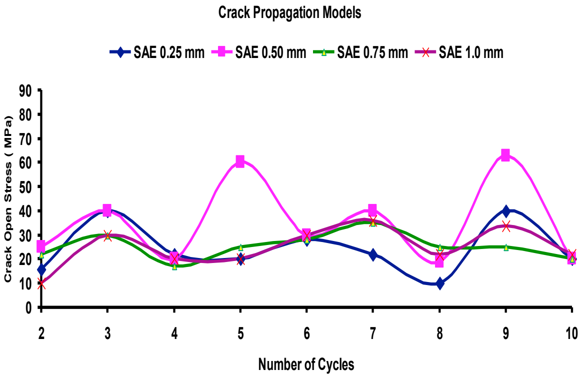

Fig. 4 Crack Opening Stress

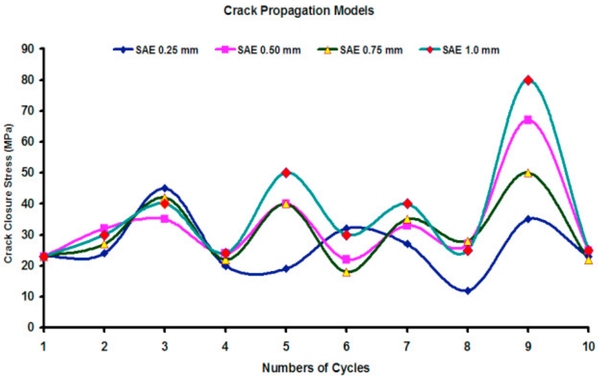

Fig. 5 Crack Closing Stress

4. Discussion of Results

In the present work it was very difficult to determine with proper precision the crack opening or closing. It was necessary to use the iteration process in the crack surface step by step during loading and unloading to find the crack opening or closing as in Ricardo (2002, 2003). The retard effect is present in some cycles in special cases where there are overloads. In constant amplitude loading, the effective plastic zone increases with the extension of the crack length; the crack propagation rate has no influence in the quality of results, assuming that it is in respect to the Newman (1974) recommendation with four elements yielded in the reverse plastic zone. In variable amplitude loading the crack length cannot progress until a new overload occurs or the energy spent during cyclic process creates a new plastic zone and the driving force increases the crack length. The researchers normally work with simple overloads or specific load blocks; this approach can induce some mistakes in terms of results that can be conservative or nonrealistic. Fig. 4 shows the effect of different crack propagation rates in open stress, $\sigma_{op.}$ This graph starts in the second cycle because it was not possible identify the crack opining in all models evaluated when crack the open, because all stresses in the first cycle were positive. In the beginning there is no representative difference in the four first cycles in all crack propagation models. In the fourth to fifth cycle it is possible identify a difference of crack open stress level from model SAE2 (crack propagation 0.5 mm/cycle) and the others models. The difference of the crack open stress level from model SAE2 from the others may be related with the overload that the specimen had in the fifth cycle causing the increase of the crack opening stress level to be more representative than in others that suffered the same overload. From the sixth to eight cycles it is possible to identify again little difference in the crack opening stress of the models. The model SAE1 (crack propagation 0.025 mm/cycle) has the lower crack opening stress. In the cycles 8 to 10 there is some difference in the crack opening stress, having as principal cause the different plasticity that the models suffered, due to different crack propagation rate models. Model SAE2 has the bigger crack opening stress; caused like in the fifth cycle by an overload as in the fifth cycle and again this model had different behaviour when compared with others models. The model SAE3 (crack propagation rate 0.75 mm) has no significant difference in the crack opening stress level during all cycles. This could be a good indication that for a first approach in similar conditions the utilization of this crack propagation rate will provide the behaviour material faster under similar load history and specimen. Fig. 4 also shows that it is possible to have more different kinds of criteria design. For example for a conservative approach it is possible the utilization of the model SAE1 (crack propagation rate 0.025 mm/cycle) is possible. Fig. 5 presents the results from the crack closing stress by numbers of cycles evaluating four different crack propagation models. It is possible to observe that in the first four cycles there are no significant difference in the crack closing stress in the models studied. In the others cycles the model SAE1 (crack propagation 0.025 mm/cycle), has no significant difference of crack closing stress during crack propagation. In fact it is the most conservative model from the four evaluated. During the fourth and sixth cycle the models SAE2 (crack propagation model 0.50 mm) and SAE3 (crack propagation model 075 mm) have no difference in the crack closing stress. The model SAE4 (crack propagation 1.0 mm/cycle) has representative difference in the crack closing stress when compared with others models in the cycles due to more residual plasticity in the crack tip. The last representative differences between crack closing stress levels in the models happen during propagation in the cycles eight to tenth. The effect of the residual plasticity is shown in all models. An increase of the crack propagation rate will also increase also the crack closing stress. Figs. 4 and 5 show that depending on the design criterion it is to possible applying a different crack propagation rate. For example if the criterion is to use a conservative crack closing stress it is recommended utilization of the model SAE1 (crack propagation 0.025 mm). The softest model or that allows the bigger crack opening and closing stresses is model SAE4 (crack propagation model 1.0 cycle/mm).

5. Conclusion

In this work it was possible to identify the crack opening and closure using the finite element method. In the literature there are few works covering crack propagation simulation with random loads like FD&E loads histories from SAE data bank. Normally only a few load blocks are used to reduce the complexity; this should provide conservative answers when used to develop structural components. The use of different crack propagation rates in this work shows that is possible to reproduce the effective plastic zone. It is possible also to use smaller or larger element sizes compared with element size estimated by Irwin equation. To fix the correlation it is necessary to increase the crack length to obtain the same qualitative results than estimated by the Irwin equation. The next step in this work will be to perform the same model and load history with different crack propagation rates to identify or not if the retard effect can be observed. These data will be compared with experimental test and, if necessary, adjustment of the crack propagation model will be done to improve the crack propagation model results and consequence correlation with experimental data.

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