FATIGUE LIFE AND CRACK GROWTH ANALYSIS OF KEYHOLE SPECIMEN

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LIST OF SYMBOLS

N_f	fatigue life
σ'_f	fatigue strength coefficient
E	modulus of elasticity
b	fatigue strength exponent
ε'_f	fatigue ductility coefficient
c	fatigue ductility exponent
K_{IC}	fracture toughness
ΔK	crack tip intensity factor
ΔK_{th}	stress intensity factor range
ΔK_{eff}	stress intensity factor range
da/dN	crack propagation rate
β	crack inclined angle
θ_o	crack growth direction
E	Young’s modulus
S_U	Ultimate tensile strength
σ'_f	Fatigue strength coefficient
b	Fatigue strength exponent
ε'_f	Fatigue ductility coefficient
c	Fatigue ductility exponent
s_f	Fatigue strength
$k^{'}$	Cyclic strength coefficient
$n^{'}$	Cyclic strain hardening exponent

LIST OF ABBREVIATIONS

LEFM	linear elastic fracture mechanics
S-N	total-life
SAETRN	tensile mean loading history
SAESUS	compressive loading history
SAEBKT	zero mean loading history
SEM	scanning electron microscopy
BEM	Boundary Element Method
SWT	Smith-Watson-Topper
CAD	computer-aid design
PSB	persistent slip band
FEA	finite element analysis
SAE	Society of Automotive Engineers

ABSTRACT

This report deals with the prediction of fatigue life and crack growth for keyhole specimen using variable loading amplitude. The objective of this report is to predict the fatigue life and crack growth of keyhole specimen. The steel such as MANTEN and RQC100 were considered the keyhole materials. The structural three-dimensional solid modeling of keyhole specimen was developed using Solid work. The finite element model and analysis were performed using PATRAN and NASTRAN software. Predicted result is validated with existing experimental result. In addition, the fatigue life was predicted using the strain-life approach subjected to variable amplitude loading. From the results, it is observed that SAETRN loading gives the most conservative results for strain-life method. It is concluded that SAETRN loading history is the most conservative method compared to SAESUS and SAEBKT loading history. RQC100 has a longer crack initiation life but shorter crack propagation life than MANTEN. Apparently, MANTEN more ductile than RQC100. The RQC100 is suitable material of keyhole.

ABSTRAK

Tesis ini membentangkan penyelidikan ramalan menggunakan unsur terhingga berasaskan pengkomputeran bagi menilai kebolehtahanan terhadap lubang kunci menggunakan beban amplitut berubah. Objektif laporan ini ialah untuk memprediksi umur keletihan dan pertumbuhan retak model lubang kunci. Besi seperti MANTEN dan RQC100 digunakan sebagai bahan untuk lubang kunci. Permodelan struktur pejal tiga-dimensi bagi lubang kunci dibangunkan dengan perisian lukisan bantuan komputer. Analisis unsur terhingga dijalankan dengan kod PATRAN dan NASTRAN. Keputusan ramalan dibandingkan dengan keputusan experiment yang telah wujud. Hayat kelelahan dijangka menggunakan pendekatan strain-hidup dikenakan beban amplitut berubah. Keputusan yang diperolehi menunjukkan SAETRN meramalkan hayat konsevertif. Ini menunjukkan SAETRN merupakan cara yang paling conservative kalau dibandingkan dengan SAESUS dan SAEBKT. RQC100 mempunyai retak awal kehidupan yang lebih panjang tapi retak kehidupan yang lebih pendek berbanding dengan MANTEN. MANTEN lebih elastik daripada RQC100. Jadi, RQC100 adalah bahan yang lebih sesuai untuk lubang kunci.

CHAPTER 1

INTRODUCTION

1.1 INTRODUCTION

In mechanical industry, the prediction of fatigue life in the high stress/strain field (relatively low number of cycles) is becoming more widespread. This is due to the increasing demand for improved performance in mechanical components. Design is becoming steadily oriented to more complicated shapes, which introduces more stress risers (usually reported as notches), and to lighter geometries, especially in fields such as the aircraft or automotive industries. The prediction of the fatigue life of specimens loaded under variable amplitude conditions is a complex subject. In the early 1960s it was shown that the low-cycle fatigue behaviour of metals is dominated by the strain, rather than by the stress as assumed previously. In fact, when a sharp notch occurs in a component, the effect on the stress field is so heavy that often the material yields locally. In such a case the quantity that must be used to describe the material behaviour is the local strain, so it is necessary to carry out a life prediction based on the strain-fatigue properties. From these considerations a method called the "Local Strain Approach" was proposed. Its main points can be summarised as (i) the actual strain at the notch root is evaluated. The most important method to solve this problem was proposed by Neuber (1961), and is still widely used;(ii) the prediction of the component life is made using strain based fatigue life law. This approach to low-cycle fatigue life was proposed by Manson and Coffin (1954). This methodology studies only the behaviour of the material at the notch root, so that the predicted life is referred to a small part of the resisting section, in the neighbourhood of the notch. The failure is assumed to occur when a relatively small crack appears at the notch root.

Other works on the evaluation of the local strain have been published, mainly because the Neuber's method gave a large conservatism on the predicted life. Furthermore the latter does not have a theoretical basic, but is based only on experimental observations on notched components. With modern computing facilities it is possible to assess the local strain using a numerical method, mainly Finite Element Analysis, when the load history is very simple, such as a sinusoid between two fixed values. Another source of conservatism is the fact that the Local Strain Approach neglects the remaining life of the component needed to extend the crack up to the real failure, which for some geometries can be a large part of the total life. The phenomenon of the crack growth has been studied from the early 1900s, and its analysis is based on the law proposed by Paris (1961). The chief aim of the project is to evaluate the importance of using a combined approach, to predict the two parts of the life. Moreover, a comparison of the methods (Neuber method, Finite Element Analysis, and Energy based method) now available to assess the local strain is carried out in order to find out which of them is more accurate and suitable in different load situations.

The fatigue life until failure has been divided into two periods: (i) the crack initiation period, and (ii) crack growth period. Crack nucleation and microcrack growth in the first period are primarily phenomena occurring at the material surface. The second period starts when the fatigue crack penetrates into the subsurface material away from the material surface. The growth of the fatigue crack is then depending on the crack growth resistance of the material as a bulk property. The fatigue life of an unnotched specimen in the high-cycle fatigue regime is largely covered by the crack initiation period. The crack growth period could almost be disregarded and often is ignored. Under which condition is crack growth in the second period of practical interest? Obviously, the load spectrum should contain stress cycles above the fatigue limit in order to have a problem of fatigue crack growth. Secondly some macrocrack growth must be acceptable ,or, as phrased in a different way, some crack growth might be unavoidable, and it should then be known how fast crack growth occurs. Two well-known examples are: (i) crack growth in sheet material where the crack is growing through the full thickness of the material. An obvious example is fatigue crack growth in aircraft skin structures; (ii) a second example is the growth of part through cracks where a corner crack and a surface crack start at a hole. Another example is the occurrence of surface cracks starting at the toe of a weld in a welded structure. In many practical cases, part through cracks are associated with either massive components or with thick plate structures.

The prediction of the fatigue life of specimens loaded under variable amplitude conditions is a complex subject. The most widely used theory is the linear damage rule commonly referred to as the Miner rule (Miner, 1945). The *S–N* curve is the only information needed for the Miner rule. However, in many cases it leads to inaccurate, often non-conservative life predictions. The reason for this is the different load-dependency of the crack initiation and the crack growth phase. A comprehensive review paper providing an overview of cumulative damage theories for metals and alloys has been published recently (Fatemi and Yang, 1998). Most theories wish to gain a high improvement of the life prediction accuracy by only adding little information in excess of the *S–N* curve. Three of these theories (Subramanyan, 1976; Hashin, 1980; Manson and Halford, 1981) use a power-law damage rule to account for the load sequence effects. In this paper a new exponent for the power-law damage rule has been determined. Load interaction effects such as crack growth retardation after overloads are not taken into account. Instead of calculating the transition point between the crack initiation and the crack propagation phase, a steady change in the damage accumulation speed is considered.

1.2 PROBLEM STATEMENT

Crack can be acceptable for different reasons. It may be that crack does not have significant safety or economic consequences. The more cases arrive if safety, or economy, or both are involved. This occurs in pressure vessels if a leak from a fatigue crack can lead to an explosion. Another category of problems is related to fatigue crack growth monitored by periodic inspections. The purpose of the inspection is to discover fatigue cracks before they become dangerous. It then is necessary to know how fast a crack is growing in order to set timely inspection periods. The keyhole is subjected to cyclic loading. The keyhole, uncertainly is related to loads expected given to the component due to individual usage style and environment conditions. The best design

REFERENCES

Anthony, W.T. 1975. Fatigue crack propagation in Austenitic Stainless Steel. *Engineering Fracture Mechanics.* 7:61-68

Bian, L. 2009. Crack growth prediction and non-linear analysis for an elasto-plastic solid. *International Journal of Engineering Science.* 47:325-341

Coffin, L.F. and Manson, S.S. 1954. A study of the effect of cyclic thermal stresses on a ductile metal. *Transactions of ASME*. 76:931-950

Fatemi, A. and Yang, L. 1998. Cumulative fatigue damage and life prediction theories: a survey of the state of the art for homogenous materials. *International Journal Fatigue.* 20:9–34

Hashin, Z. 1980. A reinterpretation of the palmgren–miner rule forfatigue life prediction. *Journal Applied Mechanics Transactions of ASME*. 47:324–8

Miner, M. 1945. Cumulative damage in fatigue. *Journal Applied Mechanics*. 68:339–41

Manson, S and Halford, G. 1981. Practical implementation of the doublelinear damage rule and damage curve appoach for treating cumulative fatigue damage. *International Journal Fracture* .17:169–92

Neuber, H. 1961. Theory of stress concentration for shear-strained prismatical bodies with arbitrary nonlinear stress–strain law. *Journal Applied Mechanics.* 28:544–550

Paris, P.C. and Erdogan, F. 1963. A critical analysis of crack propagation laws. *Transactions of ASME, Series D*. 85: 528-535

Paris, P.C., Gomez, M.P. and Anderson, W.E. 1961. A rational analytical theory of fatigue. *The Trend of Engineering*. 13:9-14

Purbolaksono, J., Ali, A.A., Khinani, A. and Rashid, A.Z. 2009. Crack Growth analysis of wide flange I-beam under constant amplitude bending loadings. *American Journal of Scientific Research*. ISSN 1450-223X (3): 67-74

Rahman, M.M., Ariffin, A.K., Abdullah, S. and Jamaludin, N. 2007. Finite element based durability assessment of a free piston linear engine component. *Technology Science Press*. SDHM, 3(1): 1-13

Rahman, M.M., Ariffin, A.K., Abdullah, S. and Rosli, A.B. 2007. Effect of nitriding treatment on fatigue life for free piston linear engine component using frequency response method: a finite element approach. *Technology Science Press*. SDHM, 3(4): 197-209

Rahman, M.M., Ariffin, A.K., Jamaludin, N., Abdullah, S., and Noor, M.M. 2008. Finite element based fatigue life prediction of a new free piston engine mounting. *Journal of Applied Sciences*. ISSN 1812-5654 8(9): 1612-1621

Rahman , M.M., Ariffin, A.K., Abdullah, S., Noor, M.M., Bakar, R.A. and Maleque, M.A. 2008. Finite element based fatigue life prediction of cylinder head for two-stroke linear engine using stress-life approach. *Journal of Applied Sciences.* 8(19): 3316-3327

Xu, D.K., Liu, L., Xu, Y.B. and Han, E.H. 2007. The fatigue crack propagation behavior of the forged Mg-Zn-Y-Zr alloy. *Journal of Alloys and Compound*. 431:107–111

Young, H.K., Song, J.H., and Park, J.H. 2009. An expert system for fatigue life prediction under variable loading. *Expert System with Applications: An International Journal*. 36: 4996-5008

Subramanyan, S. 1976. A cumulative damage rule based on the kneepoint of the S–N curve. *Journal of Engineering Material & Technology*. 98:316–21

Thompson, A.W. 1972. *Metallography.* 5:366-369

Thompson, A.W. 1974. *Material Science Engineering.* 14:254-263

Tucker, L. and Bussa, S. 1977. *Fatigue Under Complex Loading: Analysis and Experiments*. 1st Edn., Society of Automotive Engineers, Warrendale, PA. pp:3-14