FATIGUE AS A DESIGN CRITERION

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Preface

The majority of research studies in the field of metal fatigue or progressive fracture have been mainly concerned with fundamental investigations into the basic mechanism, or have concentrated on the specific assessment of various factors. Consequently, although the literature available dealing with the subject is immense and continues to increase at a tremendous rate, it remains a fact that the application of fatigue data to design situations has not received such great attention, and it is still common practice to carry out fatigue tests on actual components.

The basic objective of this book is that of establishing methodical procedures for the application of fatigue data to design. In so doing, the mechanical behaviour of materials, the factors which influence such behaviour and the application to real components are discussed.

In assessing the fatigue integrity of components, due consideration must be given to stress-strain analysis, crack formation, fatigue crack growth and final fracture. All these aspects are dealt with in detail, and some new research data and original theory are also included. The work is based on experience gained over a considerable period of time, both as a research activity, and also in teaching the subject at both under- and post-graduate level to engineering students.

This book is not intended to supersede the various excellent texts dealing with particular aspects of fatigue. However, every effort has been made to ensure adequate coverage of both high and low cycle fatigue; multiaxial stress systems subjected to cyclic loading; simple creep-fatigue considerations; cyclic material behaviour; metallurgical aspects of fatigue; the assessment of crack formation life; fracture mechanics and its application to fatigue crack growth and fast fracture; and the influence of environmental factors. Each chapter includes an extensive and comprehensive list of references, and the reader who studies this work will be in a strong position to read the most current research papers associated with fracture and fatigue.

It is hoped that the book will appeal to research workers, stress analysts, design engineers and metallurgists. Additionally, the book has been written to satisfy the requirements of most mechanical engineering degrees and diplomas which include the mechanical behaviour of materials, and it should provide a useful background text for adoption in many University and Polytechnic Departments. Indeed, in supervising final year student projects in this field over the past decade, the need for a single comprehensive but simple text has become apparent, and we sincerely hope that this book will go at least part way to satisfy this need.

It should be mentioned that the material presented here has been used most successfully, in note form, as the basis for short post-graduate courses operated in the Department of Mechanical Engineering at Portsmouth Polytechnic. Consequently, we would like to thank our colleagues in the Mechanical Behaviour

of Materials Group for their valuable assistance in both direct and indirect ways, as well as our industrial collaborators, particularly our friends at Rolls Royce Ltd. associated with mechanical integrity and materials engineering. Finally, we wish to record our thanks to the publishers, and all associated with the production of the book, for their care, interest and cooperation throughout. Any criticisms of the work should, of course, be directed to the authors!

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T.V.D.
J.B.

Notation

A	{ material constant cross sectional area
A_1 A_2 A_3 }	constant coefficients
a	{ half crack length for central crack crack length for edge crack half length of minor axis of ellipse hole radius Neuber material constant
a_c	critical crack length
B	{ material constant specimen thickness
b	{ material constant half length of major axis of ellipse
C	{ material constant creep rate
C_e	strain range corresponding to elastic intercept for one cycle
C_L	factor to allow for type of loading
C_p	{ strain range corresponding to plastic intercept for one cycle condition for non-propagating crack
C_s	factor to allow for size effects
C_1 C_2 C_3 }	creep rates in directions of principal stress
c c_1 c_2 c_3 }	material constants
c_1 c_2 c_3 }	combined material and geometric constants
D	{ damage factor logarithmic ductility
da/dN	fatigue crack growth rate
E	elastic modulus
E_s	secant modulus
F	{ material constant used to describe stress–strain behaviour constraint factor
f	{ function frequency
G	elastic modulus in shear
$\mathcal{G}$	strain energy release rate

g	material constant
$\left. \begin{matrix} I_1 \\ I_2 \\ I_3 \end{matrix} \right\}$	stress invariants
K_c	critical stress intensity factor
K_f	fatigue strength reduction factor
K_{fs}	fatigue strength reduction factor in shear
K_s	factor to allow for surface finish effects
K_t	theoretical or geometric stress concentration factor
K_{ts}	theoretical or geometric stress concentration factor in shear
K_{max}	maximum stress intensity factor
K_{min}	minimum stress intensity factor
K_ϵ	strain concentration factor
K_σ	stress concentration factor
K_I	stress intensity factor for mode I opening
K_{II}	stress intensity factor for mode II opening
K_{III}	stress intensity factor for mode III opening
K_{IC}	plane strain fracture toughness
K_{ISCC}	threshold stress intensity in specific corrodent
k	material constant
M	bending moment
m	material constant
N	number of applied cycles
N_f	number of cycles to failure
N_c	number of cycles to give critical condition
n	material constant
p	numerical exponent
Q	flaw shape parameter
q	$\left\{ \begin{matrix} \text{numerical exponent} \\ \text{notch sensitivity index} \end{matrix} \right.$
q_s	notch sensitivity index in shear
R	bulk stress ratio
RA	reduction in area
RF	reserve factor
RF_a	reserve factor for alternating stress
RF_m	reserve factor for mean stress
r	notch radius
r_p	plastic zone radius
r_ϵ	localised strain ratio
r_σ	localised stress ratio
S	surface energy
S_a	intrinsic fatigue strength corresponding to any number of cycles for completely reversed loading
S'_a	component fatigue strength corresponding to any number of cycles for completely reversed loading
S_e	intrinsic fatigue or endurance limit for completely reversed loading
S'_e	component fatigue or endurance limit for completely reversed loading
S_c	critical strength of material or component

S_f	fatigue strength coefficient
S_p	monotonic yield or proof strength
S'_p	cyclic yield or proof strength
S_{sa}	intrinsic fatigue strength in shear corresponding to any number of cycles for completely reversed loading
S'_{sa}	component fatigue strength in shear corresponding to any number of cycles for completely reversed loading
S_{sp}	monotonic yield strength in shear
S_{su}	ultimate strength in shear
S_u	ultimate tensile strength
S_w	working strength
T	failure time at particular load condition
t	{ thickness time duration of applied loading
U	strain energy
W	specimen depth
x	linear co-ordinate
Y	compliance function
Y_0	modified compliance function
y	linear co-ordinate
z	linear co-ordinate
α	material constant
α_1	slope of plastic strain with cycles on logarithmic plot
α_2	slope of elastic strain with cycles on logarithmic plot
β	angle measured around crack front
γ	shear strain
γ_s	surface strain energy per unit area
γ_p	plastic work factor per unit area
ΔK	stress intensity range
ΔK_I	stress intensity range for mode I opening
ΔK_{ITH}	stress intensity range below which fatigue cracks remain dormant
ΔK_{Io}	threshold stress intensity range
$\Delta \epsilon$	strain range
$\Delta \epsilon_e$	elastic strain range
$\Delta \epsilon_a$	endurance strain range
$\Delta \epsilon_{e0}$	elastic strain range with zero mean stress
$\Delta \epsilon_{L0}$	strain range equivalent of endurance or fatigue limit for zero mean stress
$\Delta \epsilon_T$	total strain range
$\Delta \sigma$	localised stress range
$\Delta \sigma_0$	nominal or bulk stress range
δ	critical depth of material required to produce failure
ϵ	strain amplitude
ϵ_1	} principal strains
ϵ_2	
ϵ_3	
ϵ_c	strain amplitude corresponding to critical condition
ϵ_f	fracture strain

ϵ_f'	fatigue ductility coefficient
ϵ_{end}	endurance or fatigue limit strain equivalent
ϵ_m	mean strain
ϵ_{max}	maximum strain amplitude
ϵ_{min}	minimum strain amplitude
ϵ_0	nominal strain amplitude
ϵ_{yp}	yield strain
θ	polar co-ordinate
ν	Poisson's ratio
ν_e	Poisson's ratio in elastic region
ν_p	Poisson's ratio in plastic region
ν'	modified Poisson's ratio to allow for some degree of plasticity
ρ	notch radius
σ	direct stress
σ_{alt}	alternating component of direct stress
σ_{alte}	equivalent alternating component of direct stresses
σ_e	equivalent stress amplitude
σ_f	fracture stress
σ_m	mean component of direct stress
σ_{me}	equivalent mean component of direct stresses
σ_{max}	maximum stress amplitude
σ_{min}	minimum stress amplitude
σ_0	nominal or bulk stress amplitude
σ_s	equivalent static stress replacing cyclic stresses
$\left. \begin{matrix} \sigma_1 \\ \sigma_2 \\ \sigma_3 \end{matrix} \right\}$	principal stress amplitudes
τ	shear stress
τ_{alt}	alternating component of shear stress
τ_m	mean component of shear stresses
τ_{max}	maximum shear stress amplitude
τ_{min}	minimum shear stress amplitude
$\left. \begin{matrix} \tau_{12} \\ \tau_{13} \\ \tau_{23} \end{matrix} \right\}$	maximum shear stress amplitudes
ϕ	$\left\{ \begin{array}{l} \text{plasticity modulus} \\ \text{elliptic integral} \end{array} \right.$