

UNIVERSITY OF THE WITWATERSRAND, Johannesburg

SCHOOL OF MECHANICAL ENGINEERING



TENSILE FATIGUE OF NOTCHED CARBON/EPOXY SPECIMENS

KONSTANTINOS DIAMANTAKOS

A dissertation submitted to the Faculty of Engineering, University of the Witwatersrand, Johannesburg, in fulfilment of the requirements for the degree of Master of Science in Engineering.

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DEDICATION

To my parents Sunday and Alex in appreciation for their understanding
throughout my education

and

To my wife Yvonne for her love and support

DECLARATION

I declare that this thesis is my own, unaided work. It is being submitted for the Degree of Master of Science in Engineering in the University of the Witwatersrand, Johannesburg.

It has not been submitted before for any degree or examination in any other University.



G. DIAMANTAKOS

(Signature of Candidate)

14th

day of

AUGUST

198 6

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- * MR F A S BEZUIDENHOUT - Superintendent of the Mechanical Engineering Laboratory, University of the Witwatersrand for his assistance during the preparation of the test specimens employed for the thesis.
- * The Composite's department from CSIR (NIAST)

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List of Symbols

Definitions

A, A'	Constant, Batch number
a	Crack length
B	Constant, Batch number, Gauge length
b	Width of parallel waisted specimen
C	Constant, width of specimen, Batch number
D	Constant, Batch number
d	Fibre diameter
E	Young's modulus, Reduced stiffness, Batch number, length between grips of specimen
E_o	Original stiffness
E_{eff}	Effective stiffness of isotropic plate
E_m	Young's modulus of matrix
E_f	Young's modulus of fibre
E_L	Young's modulus of laminate
E_T	Young's modulus of laminate in the transverse direction
e	Strain, exponential power
F	Function
f	Fibre, length of specimen
G	Strain energy release rate
G_I	Strain energy release rate for orthotropic plates
G_M	Shear modulus of matrix
G_f	Shear modulus of fibre
G_A	Shear modulus
h	Thickness of specimen
K	Stress concentration factor, misalignment factor
K_I	Stress intensity factor
L, L_o	Specimen length, gauge length distance between fibre centres, fibre length
ℓ	Initial length of fibre
N_o	Number of chains
N_T	Total number of broken fibres
n	Number of fatigue cycles
Q	Load
R	Radius, strength reduction factor, stress level

S	Strength, standard deviation
S_K	Composite strength
S_f	Fibre strength
S_m	Matrix strength
t	Thickness
V	constant
V_f	Volume ratio of fibres
V_m	Volume ratio of matrix
UT	Total strain energy
U_{nc}	Energy due to applying load with no crack present on a plate
W	Width of plate or a specimen
X	Individual test result, distance
Y	Constant, Finite width correction factor,
Z	Section of specimen
Z_o	Half thickness of the neck of a waisted specimen

Greek Symbols

Definitions

α	constant
β	power constant
Δ	Total displacement
Δ_{nc}	Displacement with no crack present on a plate
δ	length of fibre
$\bar{n}$	Total number of tests
ν	Poisson's ratio
π	constant
σ	stress
σ_t	Tensile stress
σ_c	Compressive stress
σ_{11}	Stress in parallel
σ_L	direction or longitudinal
σ_{1t}	Stress in transverse direction
σ_{1c}	Tensile stress in transverse direction
σ_a	Compressive stress in transverse direction
σ_u	Stress amplitude
σ_f	Static strength
σ_f^*	Applied stress on fibre
$\sigma(\delta)$	Stress supported by intact fibres, stress of fibre at distance δ
τ	Shear
τ	Shear in Cross. Parallel and perpendicular to the fibres
τ^*	Total shear
ϕ	Stress of fibre/stress of fibre at distance of δ

ABSTRACT

A number of experimental data on fatigue of metals is available both to engineers and designers.

In the case of fibre reinforced plastics much of these relate to unidirectionally reinforced plastics, but there is also some information on the behaviour of laminates of variable ply geometry.

Measurements have been made of fatigue response under cyclic tensile, compressive, flexural, torsion and shear loading, but the establishment of a universal model for investigating fatigue has still to be done. In this paper the fatigue of notched specimens of different notch size but of the same geometry is being investigated as well as the parameters influencing the behaviour of the specimens.

The fatigue crack initiation is recorded by using a wire technique as well as a photomicrographic technique. The inconsistent fatigue behaviour may be due to the observed manufacturing irregularities and high stress concentrations at the root of the notches.

Recommendations are given as to which mode should be used for further fatigue tests on notched specimens.

Finally it can be noted that the main failures occurring are matrix cracking for the double waisted ones along the width while in the other case tensile failure is the main failure mode.

The point of initiation of the specimen failure appears to be at the outer surface.

CHAPTER 1

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1.1 Introduction

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1.2 Outline of this Study

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INTRODUCTION

Despite the widespread commercial use of advanced composite materials, especially in the aerospace industry, there exist a number of key areas where insufficient knowledge and understanding still inhibit efficient design.

A recent survey by the American Institute of Aeronautics and Astronautics (AIAA) Composite Structures Subcommittee, of a wide cross section of advanced composite users, revealed little agreement on what constitutes a structural failure, and how to predict it. One of the areas of concern also was the use of empirical formulae for prediction of fatigue life and their reliability.

Though the understanding of different kinds of damage, and their interaction under static and fatigue loading has increased markedly little is known about the behaviour of fatigue and the rate of damage growth.

For example, lifetime predictions based on the linear Miner's Rule damage summation are non-conservative.

Outline of this Study

It is the objective of this study to establish an empirical formula for notched unidirectional carbon/epoxy specimens. A brief review of the relevant work from the considerable literature available on the subject of fatigue and damage in composites is presented in chapter 2.

The relevant theory on fatigue of carbon/epoxy specimens is described on chapter three even though the failure criteria and empirical formulae mentioned have still to be proved due to lack of enough experimental data.

Chapter four covers the discussion and various conclusions that were reached during experimentation and it is indicated that the empirical formulae proposed by various authors apply to a certain type of notched unidirectional carbon/epoxy specimens while the other type of notched specimens behaves in a completely different manner. Matrix cracking and tensile failure are the main failures occurring during testing.

Appendix A covers the tooling incorporated for the machining as well as the laying up techniques, Appendix B covers successively tensile and fatigue results.

Appendix C refers to tables and finally appendix D covers the description of the apparatus used.

Graphs, figures and references are given in appendix E.

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LITERATURE SURVEY

A considerable volume of literature concerned with the mechanical behaviour of fibre reinforced composite materials exists, and no survey can be expected to cover all aspects of this published work.

The short survey is a summary of the generally accepted views on the nature of damage in composite laminates, its accumulation in order of fatigue loading as well as the empirical formulae justifying the data available.

More detailed and specific views can be found in Hashin¹ (1983) Rosen² (1982), Reifsnider and Drake³ (1982) and Salamon⁴ (1980).

2.1 Nature of Damage

Damage in a laminate under tensile loading may be split into two broad categories (Nuismer and Tan, 1982)⁵

(i) Matrix cracking

The first damage normally observed is the multiple cracking of the off axis plies. The crack spacing is a function of the applied load (eg Garret and Barley 1977)⁶ and the laminate stacking sequence and properties (Highsmith and Reifsnider 1982)⁷ (Bader N G and Boniface)⁸

The crack spacings appear to stabilize at a unique value for a given ply in a laminate (Broutman and Sahu, 1969)⁹ in a pattern which Reifsnider¹⁰ has called the 'Characteristic Damage State' (CDS).

It is possible to suppress matrix cracking, by using very thin plies. There is a stiffness reduction associated with matrix cracking. The maximum reduction can be estimated by discounting the cracked ply properties from a laminated plate theory analysis of the system (Highsmith and Reifsnider, 1982)¹¹.

Matrix cracking in the unidirectional laminates parallel to the loading direction, is generally called 'splitting', and is similar to matrix cracking.

(ii) Fibre breakage and debonding

Dispersed fibre breakage occurs under fatigue loading (Roderick and Whitcomb, 1975, Freeman 1982)¹²

There appears to be a higher concentration of breaks in the vicinity of matrix cracks than elsewhere (Reifsnider and Jamison, 1982)¹³.

However, the density of fibre breaks drops off quickly with distance from the crack tip. Reifsnider and Highsmith (1981) calculated that there is little stiffness reduction due to fibre breakage. However, recent work by them, which allows for debonding along the fibre, suggests that measurable stiffness reductions can be achieved.

O'Brien and Reifsnider (1977)¹⁴ correlated matrix cracking and debonding near fibre breaks with stiffness changes in the laminate, and showed that the strength of the laminate decreases with increasing density of fibre breaks.

In summary, the sequence of damage accumulation appears to be the initiation and growth of matrix cracks and delaminations, followed by fibre breakage, splitting, debonding and crack coupling, eventually, localisation of damage occurs and failure of the specimen ensues.

Apart from the growth of delaminations, there is little known about the parameters affecting the rate of growth of damage.

2.1 Life Prediction

A critical review of life prediction models can be found in Gordon and Whitehead (1979)¹⁵. A common approach to the accumulation of damage in fatigue is to consider the decrease in residual strength with cycling (Rosen 1982, Reifsnider et al, 1982). The S-N curve is considered to be the locus of the points where the residual strength curves equal the applied stress.

One of the earliest approaches to life prediction is the 'wear-out' model of Halpin, Jerina and Johnson (1973)¹⁶ and Halpin, Johnson and Waddoups (1972)¹⁷.

This model attempts to predict the residual strength at any stage, from a known initial static strength. It assumes that the damage accumulation, or decrease in the residual strength, may be described by a power function of the applied stress.

Very little published experimental work is available to verify the theory. Any models such as the one given by Carswell (1977)¹⁸ serves to give some appreciation of the major features of the fatigue behaviour in composites while the one developed by Sun and Chan¹⁹ is based upon crack propagation in viscoelastic media and indicates that fatigue life is frequency dependent for carbon/epoxy specimens.

These models, though perhaps capable of predicting behaviour under constant amplitude loading, cannot easily be adopted to predict life times under spectrum loading.

Miner's rule severely overestimates fatigue life prediction (Gordon and Whitehead 1979, Smith and Sturgeon 1979).²⁰

Green and Pratt (1974)²¹ observed that during axial tension fatigue testing of unidirectional carbon/epoxy specimens the discrepancies observed are associated with the observed differences in the degree of surface damage in the as received fibres.

Finally Daniel (1982)²² supported the stress criterion rule by indicating the effect of hole diameter on the strength reduction and fatigue life of carbon/epoxy specimens.

In summary, though a number of models exist which are able to describe behaviour under constant amplitude loading of notched carbon/epoxy specimens, none have general acceptance or applicability.

Miner's Rule is non-conservative and the available experimental data contradictory.

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