Application of the Double Torsion Specimen to the Study of Fracture in Fibre Reinforced Plastics

by

Niven Rhys Brown

A thesis submitted in partial fulfilment of the requirements for the degree of

Doctor of Philosophy

(Engineering)

Department of Mechanical Engineering
School of Engineering
University of Auckland
Auckland, New Zealand

November 1993

Abstract

The increasing use of fibre reinforced polymers in structural components often requires an accurate assessment of the strength of the component. The strength of composite materials is usually based on the strength of an individual lamina. This is then combined in a manner depending on the orientation of the plies within the laminate. The actual failure process is often ignored in this type of analysis. Composite failure is the result of damage accumulation from a number of failure modes, in particular, fibre failure, matrix failure and failure of the interface between the fibres and matrix. Measurement of the interfacial strength requires specialised testing techniques in order to obtain accurate characterisation of the interfacial failure processes.

This research uses a double torsion specimen reinforced with fibres in a number of configurations. The testing techniques developed allow the interaction of a matrix crack with fibres, resulting in the failure of the interface. Finite element analysis has been used to gain an insight into the deformation mechanisms. A compliance change analysis has been developed so that the load in the fibres can be calculated. Results from the finite element analysis confirm the analytical procedures and show that, for the fibre/resin combination tested, the interface has a lower fracture toughness than the matrix material. The interaction between the fibres and matrix shows that the mechanism of fibre bridging inhibits the propagation of matrix cracks. This produces an apparent increase in the toughness of the composite system.

To confirm the failure processes occurring, the technique of acoustic emission has been used to monitor the development of the specimen failure. In line with other workers, it is shown that matrix failure produces low amplitude events and interfacial failure produces mid amplitude events. Fibre failure did not occur to any significant degree. This thesis shows how the contribution from the presence of an interface affects the fracture of composite materials and how, via the reinforced double torsion specimen, this contribution can be measured and interpreted.

Acknowledgements

The production of this thesis would not have been possible had it not been for the time and effort of many people. Some of them may not be mentioned here by name, but their contribution has not been forgotten. In particular, I would like to express my gratitude to the following:

- My supervisor, George Moltschaniwskyj, for his support and encouragement throughout the course of this work. His patience, thoughtfulness, wisdom and conscientiousness have been a source of great inspiration. Without his invaluable supervision and many hours spent discussing fibres, fracture, fishing and front-foot cover drives, this thesis would not have been possible. Thank you.

- Associate Professor Debes Bhattacharyya for his patience, enthusiasm and diligence in co-supervising this research work.

- Mr Terry Boyd and his team of technicians for their invaluable assistance in the experimental aspects of this work.

- The University Grants Committee for their financial assistance in the form of a Postgraduate Scholarship.

- The Yacht Research Unit, Strength of Materials Laboratory and Maskell Productions Ltd for providing financial support.

- Adhesive Technologies Ltd, Dow Chemicals and High Modulus NZ Ltd for providing materials and technical advice.

- Auckland Electric Power Board (now trading as Mercury Energy), and particularly Mr Kevin Mooney, for the use of their acoustic emission equipment.

- Industrial Research Ltd for employing me over the final stages of this project. In particular, Mr Graeme Finch for his flexibility in accommodating me and for allowing me to avail myself of their computing facilities.

- The undergraduate project students who have assisted in the experimental work: Mike Boyd, Phil Steeghs, Peter Dudson and Shane Williamson.

♦ The staff, visiting fellows and my colleagues at the University of Auckland for making postgraduate study an unforgettable experience. I would especially like to thank the members of the E-team, my office cohabitants, the gang of five: Richard, Mike, Mark and David, and, especially, my composites colleague Mark. All have helped to shape me in various ways.

♦ A special thank you to those who have tolerated my using, borrowing or begging of Macintosh time: Lynley, Henry and Barb, and, ultimately, Mike and Trish.

♦ Untold thanks must go to my parents and family for bringing me up and supporting in a plethora of ways.

♥ And the final acknowledgement must go to my wife, Lynette. Her love, and encouragement (and our Kucing) have been my inspiration over the duration of my doctoral studies. Je t'aime.

Imagination
is more
important
than
knowledge.

ALBERT EINSTEIN

Table of Contents

List of Symbols

		units
a	crack length, half crack length for centre notched plate	m
A	area of fracture, cross-sectional area	m^2
$\dot{a}$	nominal crack velocity	$m.s^{-1}$
B	thickness	m
c	crack length of embedded fibre	m
C	compliance	$m.N^{-1}$
COD	crack opening displacement	m
d	fibre diameter	m
E	Young's Modulus	Pa
F	pull-out force, work done by load, strength parameter	N, J, -
G	shear modulus	Pa
G	strain energy release rate	Pa.m
h	length used to determine crack shape factor	m
K	stress intensity factor	Pa.√m
K	torsional stiffness constant	m^4
l	length of debond	m
L	specimen length, embedded fibre length	m
n	subcritical crack growth parameter	-
N	number of cycles	-
P	load on specimen, load on fibres	N
r	fibre radius, radial coordinate, distance from crack tip	m
R	interfibre distance	m
R_o	crack resistance characteristic	Pa.m
$\dot{r}$	crack front translational velocity	$m.s^{-1}$
S	ultimate shear stress, crack shape factor	Pa, -
t	thickness	m
T	applied moment	N.m
t_n	thickness at notch	m
u	displacement	m
U	strain energy	N.m
v	displacement perpendicular to the crack surface	m
v	crack velocity	$m.s^{-1}$

w_m	moment arm from load-point to support	m
W	width of double torsion specimen, energy	m, J
X	ultimate tensile strength in the fibre direction	Pa
X'	ultimate compressive strength in the fibre direction	Pa
y	load-point displacement	m
Y	ultimate tensile strength in the transverse direction	Pa
Y'	ultimate compressive strength in the transverse direction	Pa

Greek characters

δ,Δ	load-point displacement	m
δ_f	crack opening displacement at crack front	m
σ	stress	Pa
τ	shear stress	Pa
θ	angle of twist, angle coordinate	radians
ν	Poisson's ratio	-
ϕ	angle to base of crack front translational speed	radians
$\dot{\xi}$	local crack speed normal to crack front	$m.s^{-1}$
ε	strain	-

Subscripts/superscripts

0	initial position
1	reference to section 1, reference to fibre direction
2	reference to section 2, reference to transverse direction
6	reference to in-plane shear
I	mode I fracture
II	mode II fracture
III	mode III fracture
c	critical mode, reference to cracked half specimen
d	reference to debond
f	reference to fibre
FE	reference to finite element solution
i	contracted notation index
j	contracted notation index

L	reference to ligament
m	reference to matrix, reference to mid-side nodes
P	reference to load
s	reference to in-plane shear
t	total
v	reference to vertex nodes
x	cartesian coordinate, reference to fibre direction
y	cartesian coordinate, reference to transverse direction

List of Figures

List of Tables