Delamination Growth in Composites under Fatigue Loading

Proefschrift

ter verkrijging van de graad van doctor

aan de Technische Universiteit Delft,

op gezag van de Rector Magnificus prof. ir. K.C.A.M. Luyben,

voorzitter van het College voor Promoties,

in het openbaar te verdedigen op dinsdag 22 october 2013 om 10:00 uur

door

Rafiullah KHAN

Master of Science in Mechanical Engineering, North West Frontier Province University of Engineering & Technology Peshawar, Pakistan

geboren te Tajazai, Pakistan

Dit proefschrift is goedgekeurd door de promotor:

Prof.dr.ir. R. Benedictus

Dr.ir. R.C. Alderliesten, copromotor

Samenstelling promotiecommissie:

Rector Magnificus, Voorzitter

Prof. dr. ir. R. Benedictus, Technische Universiteit Delft, promotor

Dr. ir. R.C. Alderliesten, Technische Universiteit Delft, copromotor

Prof. dr. R. Curran, Technische Universiteit Delft

Prof.dr.ir. R. Marissen, Technische Universiteit Delft

Prof.dr.ir. K. van Breugel, Technische Universiteit Delft

Prof.dr. W. van Paepegem, Universiteit Gent

Dr. C. Rans, Carleton University

ISBN: 978-90-88917-15-8

Printed in The Netherlands

Dedicated to

my Teachers, Family and Friends

SUMMARY

Delamination Growth in Composites under Fatigue Loading

By

Rafiullah Khan

Fiber reinforced composites are attractive for aerospace applications due to high specific strength and stiffness. Their use has been gradually increased to 50% by weight of the aircraft over past decades. As a consequence, modern aircraft utilize composites in the primary structures like wing skin and fuselage. The use of composites in primary structures has increased the need for reliable strength assessment methodologies.

Composites are inherent to various damage types of which delamination is the most severe type of damage. Delaminations may grow due to fatigue resulting in the stress redistribution and potentially leading to structural failure, thus making fatigue an important design concern.

Damage tolerance of aircraft structures is a key aspect in maintenance and safety of aircraft. For damage tolerant design of structures, the development of accurate delamination growth assessment tools is necessary.

Delamination growth is affected by both cyclic and monotonic part of the fatigue load cycle. The effect of monotonic part is known as stress ratio (ratio of minimum to maximum cyclic stress) effect on delamination growth, and it has been extensively studied in the literature. Chapter 2 provides a detailed review of the literature concerning the stress ratio effect on delamination growth.

The literature review shows that previous studies empirically relate delamination growth to a driving force parameter that seems not based on physical mechanisms. Studies are present where mechanisms of delamination growth have been investigated; however there is a lack of efforts to link these quantitatively to delamination growth models.

The objective of this thesis is the development of a mechanistic model for delamination growth that is based on the observed delamination mechanisms and the effects of monotonic and cyclic loadings in fatigue. The thesis is based on the hypothesis that both monotonic and cyclic loading affect fracture surface formation, which can be used for delamination growth characterization. The secondary objective of the thesis is the characterization of fracture surfaces for the effect of monotonic and cyclic loading. To limit the scope, delamination growth under mode I fatigue has been investigated in the thesis.

The approach of the thesis is experimental. Delamination growth is characterized experimentally both on macroscopic and microscopic levels, as described in chapter 3. Fatigue tests were performed on double cantilever beam (DCB) specimens to investigate delamination growth behavior under different stress ratios. Specimens were made from cured laminates of M30SC/DT120 carbon/epoxy prepregs. Crack closure during delamination

growth was investigated using a clip gauge extensometer. The effect of fiber bridging was investigated by cutting bridging fibers during delamination growth experiments. Microscopy of the fracture surfaces was performed using scanning electron microscopy. Width tapered DCB (WTDCB) specimens were used for the delamination growth tests under fatigue with constant monotonic and cyclic load during delamination extension.

Results of the fatigue tests and microscopy are presented in chapter 4. The delamination growth rate has been related to the strain energy release rate (SERR). The SERR range has been defined such that it resembles the correct analogous to the stress intensity factor (SIF) range. For constant SERR range, the delamination growth rate is higher for higher stress ratios. Crack closure was observed to occur for the lowest stress ratio applied in the tests.

Fractographic analysis of the fracture surfaces revealed broken fibers, loose fibers, hackles and striations. The striations and hackles on the fracture surfaces of WTDCB specimens were quantitatively analyzed for different combinations of monotonic load and cyclic load amplitudes. It was observed that striation spacing increased with monotonic and cyclic load. The hackle length increased with monotonic load, but decreased with the cyclic load amplitude.

Crack closure and fiber bridging marginally explain the stress ratio effect on delamination growth, as discussed in chapter 5. Crack closure increases the effective minimum load at crack tip at the lower stress ratio only. This results in higher effective stress ratio at the crack tip. In this case, the SERR range was corrected for crack closure. By plotting delamination growth rate against corrected SERR range, the data shifted to the region with higher stress ratios. To illustrate the effect of crack closure in 3D representation, delamination growth rate was plotted against SERR range and maximum SERR. It was observed that the data corrected for crack closure shifted to the higher stress ratio region, while remaining on the same crack resistance surface.

It was further observed that fiber bridging decreases the delamination growth rate. The stress ratio remains the same. It was observed that fiber bridging affects both minimum and maximum loads during fatigue resulting in same stress ratio as without fiber bridging. In a 3D representation of delamination growth rate versus SERR range and maximum SERR, the data was observed to shift to the lower delamination growth rate region due to fiber bridging.

The experimental results showed that delamination growth is not a unique function of SERR range, but also depend on the stress ratio. This implies that delamination growth depends on both cyclic and monotonic loads. A two parameter model for delamination growth was developed based on the observation of the effect of cyclic and monotonic load on the fracture surfaces. Chapter 6 describes the mechanism of delamination growth and the development of the mechanistic two parameter model for delamination growth prediction. The two parameter components in the model are superimposed rather than multiplied in agreement with the superposition of the effects of cyclic and monotonic loads observed with microscopic features on the fracture surfaces. The two parameter model for delamination growth represents a crack resistance surface for the material in the 3D coordinates of delamination growth rate versus SERR range and maximum SERR.

The model has been implemented using data from the delamination growth experiments. The surface fitting tool of the commercial software MATLAB was used to obtain the equation. To validate the model, experimental data was taken from the literature. The predictions with the model and the reported experimental observations were observed to be in good agreement.

The current model is different from previous models in that the relation between delamination growth and correlating parameters is no longer a simple fit of the experimental data by regression. The fit is rather an educated fit based on the observed contribution of monotonic and cyclic load components on fracture mechanisms. The two parameters in the model are superimposed to describe contribution of the load components. In previous two parameter models the terms were multiplied without justification using the physics of delamination growth.

The conclusions of the thesis are summarized in chapter 8. It can be concluded that the effect of monotonic load on delamination growth is not fully explained by crack closure and fiber bridging. The delamination growth should be characterized using both monotonic and cyclic load components. These load components affects delamination growth at microscopic level independent of one another. The two parameter terms in the model are added in conjunction to the superposition of the effects of these parameters on microscopic features. It is concluded that the model can be extended to the delamination growth in different modes of fracture.

TABLE OF CONTENTS

NOMENCLATURE

Symbol	Description	Unit
A	Power law constant	[-]
a	Delamination length	[mm]
a_c	Cutting thread position	[mm]
Δa	Delamination extension	[mm]
B	Plate width	[m]
b	Width of double cantilever beam specimen	[mm]
C	Compliance	[m/N]
C_o	Compliance offset	[-]
da/dN	Delamination growth rate	[m/cycle]
E_1	Longitudinal Young’s modulus	[GPa]
E_2	Transverse Young’s modulus	[GPa]
G_{cloase}	SERR at crack closure	[J/m^2]
G_{max}	Maximum SERR	[J/m^2]
G_{min}	Minimum SERR	[J/m^2]
ΔG	Arithmetic SERR range	[J/m^2]
ΔG_s	SERR range	[J/m^2]
ΔG_{eff}	SERR range corrected for crack closure	[J/m^2]
ΔG_I	SERR range under mode I	[J/m^2]
ΔG_{II}	SERR range under mode II	[J/m^2]
G_{max}	Maximum SERR	[J/m^2]
G_{Imax}	Maximum SERR under Mode I	[J/m^2]
G_{IImax}	Maximum SERR under Mode II	[J/m^2]
G_{IIImax}	Maximum SERR under Mode III	[J/m^2]

ΔG_{Tmax}	Total maximum SERR under mix mode	[J/m^2]
G_{Imin}	Minimum SERR under Mode I	[J/m^2]
G_{IImin}	Minimum SERR under Mode II	[J/m^2]
G_{IIImin}	Minimum SERR under Mode III	[J/m^2]
G_{th}	Threshold SERR	[J/m^2]
G_{Ith}	Threshold SERR under Mode I	[J/m^2]
G_{IIth}	Threshold SERR under Mode II	[J/m^2]
G_c	Critical SERR	[J/m^2]
G_{Ic}	Critical SERR under Mode I	[J/m^2]
G_{IIc}	Critical SERR under Mode II	[J/m^2]
K_{max}	Maximum SIF	[MPa.m$^{1/2}$]
K_{Imax}	Maximum SIF under Mode I	[MPa.m$^{1/2}$]
K_{IImin}	Minimum SIF under Mode II	[MPa.m$^{1/2}$]
K_{th}	Threshold SIF	[MPa.m$^{1/2}$]
K_{Ith}	Threshold SIF under Mode I	[MPa.m$^{1/2}$]
K_{IIth}	Threshold SIF under Mode II	[MPa.m$^{1/2}$]
K_c	Critical SIF	[MPa.m$^{1/2}$]
K_{IIc}	Critical SIF under Mode II	[MPa.m$^{1/2}$]
ΔK	SIF range	[MPa.m$^{1/2}$]
K_{Ic}	Critical SIF under Mode I	[MPa.m$^{1/2}$]
ΔK_I	SIF range under Mode I	[MPa.m$^{1/2}$]
ΔK_{II}	SIF range under Mode II	[MPa.m$^{1/2}$]
ΔK_{eq}	Equivalent stress intensity factor range	[MPa.m$^{1/2}$]
k	Taper of WTDCB specimen	[-]
L	Hackle length	[mm]
N	Number of cycles	[-]
P	Load	[N]

R	Stress ratio	[-]
s	Striation space	[mm]
S_l	Compliance of fully open crack	[m/N]
S_m	Compliance of segment	[m/N]
σ	Stress	[Pa]
δ	Displacement	[mm]
γ	Stress ratio parameter	[-]
υ_{12}	Poison's ratio for 12 plane	[-]
$\prod$	Potential energy	[J]