Engineering Fracture Mechanics 110 (2013) 290–299

Contents lists available at ScienceDirect

Engineering Fracture Mechanics

journal homepage: www.elsevier.com/locate/engfracmech

Fatigue crack growth and propagation along the adhesive interface between fiber-reinforced composites

Yin Huang, Yingge Bu, Liangdao Zhou, Jianguo Zhu, Huiji Shi, Huimin Xie, Xue Feng *

AML, Department of Engineering Mechanics, Tsinghua University, Beijing 100084, China

ARTICLE INFO

Article history:
Received 4 April 2013
Received in revised form 6 August 2013
Accepted 8 August 2013
Available online 23 August 2013

Keywords:
Fatigue crack
Fracture toughness
Interface of composite material

ABSTRACT

There is not yet a well-developed method to conduct *in situ* fatigue test for interface crack of composite material. This paper presents a specified loading setup based on DCB-Uneven Bending Moments (DCB-UBM) test, which can control the mixed modes of interface crack. During the loading process, CCD camera is used to *in situ* monitor and record the initiation of the fatigue crack and its growth rate. In addition, digital image correlation (DIC) method is adopted to obtain the deformation near the crack tip. Finally, the experimental results and DIC analysis demonstrate some meaningful mechanism of interfacial crack propagation for composite material.

1. Introduction

Fiber-reinforced composites such as GRFP have a widely application in aircraft, wind turbine blades and construction materials due to their high strength and excellent mechanical properties [1–5]. And high-toughness adhesives are usually used to bond two composite laminates (such as the sandwich structure) in the process of the structural design. However, these aircraft structures made of the fiber-reinforced composites are usually subjected to complicated cyclic loadings during flight, such as the aerodynamic loadings, random cyclic loadings, temperature changes and rain corrosion environments [6–8]. Thus, fatigue damage and fatigue crack initiation and growth (e.g. the delamination in laminates and adhesive joints) inevitably occur in these structures and the crack propagation may lead to catastrophic accident [7,9–12]. However, the physical mechanism of the fatigue crack for composite materials (such as the crack initiation and propagation) is not yet understood fundamentally. It is therefore very important to investigate the fracture properties of composite materials under cyclic loadings.

Various test approaches for composite materials have been proposed to test the fracture toughness. For instance, Double Cantilever Beam (DCB) test method has been widely used and standardized internationally [13–15], but it is only applicable to obtain pure mode I crack fracture toughness. End Notched Flexure (ENF) test method [16–18] is the well-known method for the determination of mode II fracture toughness because of its simplicity. However, its crack propagation is unstable. Mixed Mode Bending (MMB) test [19,20] is the most widely used method for Mixed Mode fracture toughness but its instability limits its application. DCB-UBM test [21–23] achieves a range of mode mixities as well as its crack growth under both static and cyclic loadings is stable. However, there is not yet an international standard for DCB-UBM method because of its immaturity. Therefore, it is significant to develop DCB-UBM method to determine Mixed Mode fracture toughness of composite materials, as well to analyze the crack growth and propagation under cyclic loadings.

* Corresponding author.
E-mail address: fengxue@tsinghua.edu.cn (X. Feng).

0013-7944/$ - see front matter
http://dx.doi.org/10.1016/j.engfracmech.2013.08.011

Nomenclature

M_1	bending moment applied to bottom beam of GFRP
M_2	bending moment applied to top beam of GFRP
$G_{\max}$	maximum energy release rate
G	energy release rate
$\bar{E}_1$	plane strain modulus of GFRP
$\bar{E}_2$	plane strain modulus of adhesive layer
E_{11}	Young's modulus (in the x_1 direction) of GFRP
E_{22}	Young's modulus (in the x_2 direction) of GFRP
E_2	Young's modulus of adhesive layer
μ	shear modulus
μ_{12}	shear modulus in the $x_1 - x_2$ plane of GFRP
v_{12}	Poisson's ratio in the $x_1 - x_2$ plane of GFRP
v_2	Poisson's ratio of the adhesive layer
t	the ratio of the plane strain modules
h_1	GFRP thickness
h_2	adhesive layer thickness
h_0	thickness parameter
η	the ratio of thicknesses
P	the applied loading
P_m	the average loading
P_a	the amplitude of the loading
l_1	the moment arm corresponding to M_1
l_2	the moment arm corresponding to M_2
$I_{1d},\ I_{2d-down},\ I_{2d-up},\ I_{1u}$ *and* I_{2u}	moments of inertia
σ_{xx}	normal stress (in x_1 direction)
τ_{xy}	shear stress (in $x_1 - x_2$ plane)
ε_{xx}	normal strain (in the x_1 direction)
ε_{yy}	normal strain (in the x_2 direction)
ε_{xy}	shear strain (in the $x_1 - x_2$ plane)
K_{I}	stress intensity factor in mode I
K_{II}	stress intensity factor in mode II
K	interface stress intensity factor
K^{∞}	apparent stress intensity factor for homogeneous material
ϕ	real phase angle
ψ	phase angle for homogeneous material
r	the distance from the crack tip
α, β	Dundurs' parameters
$p, \varepsilon, \omega, \Omega, \kappa, \kappa_1$ and κ_2	material constants
f	loading frequency

In combination of DCB-UBM method and DIC technique, a loading setup is developed to measure Mixed Mode fracture toughness of the adhesive interface in composite materials, which can be conducted on a standard testing machine. The mode mixity of the interface crack can be controlled by adjusting the loading position. In addition, CCD camera is used to *in situ* monitor the initiation and the propagation of the interfacial crack during the cyclic loadings. Furthermore, digital image correlation (DIC) method is applied to obtain the distribution of the stresses and strains around the crack tip. Finally crack growth rate, the singularity at the crack tip and the relation between fracture toughness and loading cycles are analyzed.

2. Experimental methods

Based on DCB-UBM test, we propose a setup used to test the interfacial crack of composite materials especially suitable for the sandwich-beam structure specimen, shown in Fig. 1a. The uncracked end of the specimen is fixed at the central support with two top beams. The beams of the cracked end of the specimen are jointed with the transverse arms hanging via two springs. In this system, the loading transfer is controlled by a wire rope, which runs from a bottom beam, to a transverse arm, then up to a top beam, to the other top beam, down on the other side and repeat the process on the back of the loading equipment to finally form a closed circle via rollers. Therefore, the uneven pure bending moments in the cracked end of the specimen can be created by applying loadings to the bottom beams with different distance between rollers on the transverse