Mechanics of Materials 80 (2015) 163–182

Contents lists available at ScienceDirect

Mechanics of Materials

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

Intersonic delamination in curved thick composite laminates under quasi-static loading

Burak Gozluklu [a,b], Imren Uyar [b], Demirkan Coker [b,*]

[a] Helicopter Group, Turkish Aerospace Industries (TAI), 06980 Ankara, Turkey
[b] Department of Aerospace Engineering and METU Center for Wind Energy, Middle East Technical University, 06800 Ankara, Turkey

ARTICLE INFO

Article history:
Received 4 November 2013
Received in revised form 2 May 2014
Available online 1 August 2014

Keywords:
Cohesive zone model
Dynamic fracture mechanics
Delamination
Composite materials
Intersonic crack growth
Finite element analysis

ABSTRACT

Dynamic delamination in curved composite laminates is investigated experimentally and numerically. The laminate is 12-ply graphite/epoxy woven fabric L-shaped laminate subject to quasi-static loading perpendicular to one arm. Delamination initiation and propagation are observed using high speed camera and load–displacement data is recorded. The quasi-static shear loading initiates delamination at the curved region which propagates faster than the shear wave speed of the material, leading to intersonic delamination in the arms. In the numerical part, the experiments are simulated with finite element analysis and a bilinear cohesive zone model. Cohesive interface elements are used between all plies with the interface properties obtained from tests. The simulations predict a single delamination initiating at the corner under pure mode-I stress field propagating to the arms under pure mode-II stress field. The crack tip speeds transition from sub-Rayleigh to intersonic in conjunction with mode change. In addition to intersonic mode-II delamination, shear Mach waves emanating from the crack tips in the arms are observed. The simulations and experiments are found to be in good agreement at the macro-scale, in terms of load-displacement behavior and failure load, and at the meso-scale, in terms of delamination initiation location and crack propagation speeds. Finally, a mode dependent crack tip definition is proposed and observation of vibrations during delamination is presented. This paper presents the first conclusive evidence of intersonic delamination in composite laminates triggered under quasi-static loading.

1. Introduction

New advances in composite manufacturing technology and high demand of light weight structures are fostering the use of composite laminates in a wide variety of shapes as primary load carrying elements. In this context, L-shaped composite laminates start to replace metallic counter-parts in aerospace and wind energy industries (Fig. 1a). The L-shaped geometry is frequently encountered in aerospace applications as flanges of ribs/spars in aircraft wings and in wind energy applications as corners of turbine blade spars. However, it has been analytically shown that once a moderately thick laminate takes a curved shape, opening radial (positive radial normal) stresses are induced due to the geometry (Lekhnitskii, 1968; Ko and Jackson, 1989, 1990). In other words, interlaminar normal stresses (ILNS) are induced at the interfaces between the plies in addition to the well-known interlaminar shear stresses (ILSS) under sectional forces P, V, and M (Fig. 1b). Consequently, mixed-mode delamination failure occurs in the curved region of the L-shaped composite laminates under operational loads (Fig. 1c). A major concern then becomes the premature failure of the parts due to the fact that conventional graphite/epoxy laminates have lower fracture toughness

* Corresponding author. Tel.: +90 (539) 640 1254.
E-mail addresses: burak.gozluklu@gmail.com (B. Gozluklu), imrenuyar@gmail.com (I. Uyar), coker@metu.edu.tr (D. Coker).

http://dx.doi.org/10.1016/j.mechmat.2014.07.013
0167-6636/

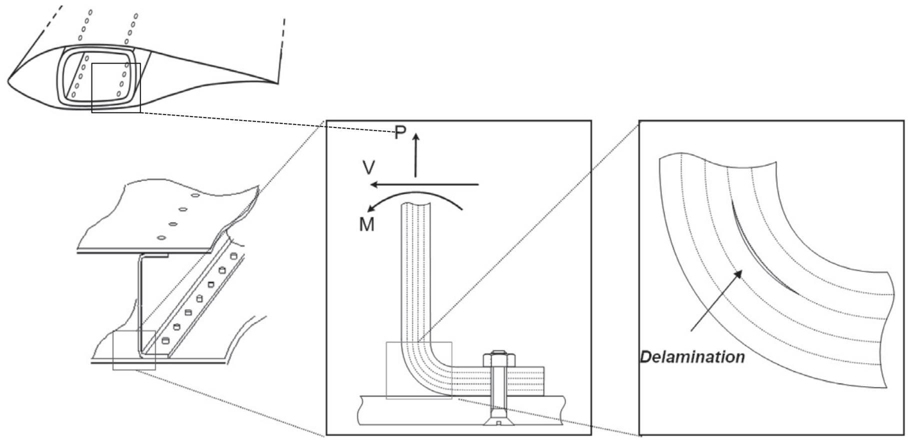

Fig. 1. (a) An example of an orthogonal structure in a wind turbine box and a wing spar/skin joint assembly with (b) the L-shaped laminate showing the section loads and (c) a delamination in the curved region.

and interfacial strength under mixed-mode loading conditions (O'Brien, 1998).

One of the earliest studies of delamination in L-shaped composite laminates was conducted by Chang and Springer (1986) where they numerically studied the influence of geometric parameters of the L-shaped beam on the failure load which was due to delamination. They also proposed a stress based quadratic initiation criterion which is also used in our study. Sun and Kelly (1988a,b) used Virtual Crack Closure Technique (VCCT) (Krueger, 2004) to obtain the energy release rate distribution on the critical interface of the curved region. Kedward et al. (1989) proposed a simple strength of materials approach that successfully estimates the maximum interlaminar stresses of delamination failure. Ko and Jackson (1989, 1990) and Hiel et al. (1991) proposed several specimen geometries to study the delamination problem in other types of curved thick composite laminates. In the early 1990's, Martin and Jackson (1991) and Martin (1992) carried out experimental and numerical investigation of the failure of L-shaped composite laminates under shear loading case, V (Fig. 1b). They showed that the initiation of delamination in the curved region is the primary failure mechanism. Martin and Jackson (1991) and Lu et al. (1994) also calculated energy release rate distribution for various geometrical and crack location configurations in the curved region. Shivakumar et al. (1994) and O'Brien and Salpekar (1991) showed that the maximum normal interfacial strength of curved beams decreases with increasing thickness and width of the specimen. Cox et al. (1996) reported that delamination under pure bending becomes stable by using through-the-thickness stitching in L-shaped composite laminates. Naji and Hoa (1999) showed that the manufacturing quality of the L-shaped composite laminates has a substantial effect on the failure load, even showing 100% change in the failure load. In 2005, Feih and Shercliff (2005) studied the failure of L-shaped composite laminates in which initially compressive matrix cracking in the inner surface of the part was encountered around one-third of the maximum load although matrix cracking did not affect the load–displacement behavior as the macroscopic failure was found to be a result of delamination. Wimmer et al. (2009a,b), Wimmer and Pettermann (2008) investigated both the initiation and propagation phases of delamination using implicit FEA and VCCT (Krueger, 2004). Since VCCT requires an initial crack to proceed, a procedure in conjunction with a stress criterion to initiate the crack was used. Wimmer et al. (2009a,b), Wimmer and Pettermann (2008) also conducted shear loading experiments and showed crack growth for small pre-cracks occurring unstably leading to dynamic fracture. In the preceding studies, static analyses have been conducted using implicit FEA which does not model the critical process of dynamic fracture. Dynamic delamination of L-shaped composite laminates was first studied numerically by Gozluklu and Coker (2012) with a pre-crack located at the middle of the laminate. They used explicit FEA in conjunction with cohesive zone modeling (CZM) at the middle interface of the laminate under quasi-static axial loading ("P" in Fig 1b). They showed cracks grew under local shear dominated loading with speeds reaching 50% of the Rayleigh wave speed (C_R). Finally, they showed that delamination occurs dynamically under mode-I, mixed-mode and mode-II conditions.

For dynamic shear dominated loading, Coker and Rosakis (2001) have shown that dynamic fracture in unidirectional composite plates occurs at intersonic speeds along the fibers with associated shear Mach waves emanating from the crack tip contrary to mode-I loading in which crack growth occurs at speeds below the Rayleigh wave speed (Broberg, 1989; Ravi-Chandar and Knauss, 1984). It complies with the fact that the crack growth can occur at speeds never exceeding Rayleigh wave speed under mode-I conditions whereas mode-II crack propagation can exceed the shear wave speed (C_s), at $\sqrt{2}C_s$ in isotropic materials (Andrews, 1976; Burridge et al., 1979; Freund, 1979) and at intersonic (super-shear) speeds up to a material dependent critical speed in composite materials (Coker and Rosakis, 2001; Huang et al., 1999; Yu et al.,