ARTICLE IN PRESS

Engineering Fracture Mechanics xxx (2017) xxx–xxx

Contents lists available at ScienceDirect

Engineering Fracture Mechanics

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

Determination of the fracture toughness of debonded asymmetric sandwich beams with a thin-walled skin considering plastic deformation

Martin Pietrek *, Peter Horst

Inst. of Aircraft Design and Lightweight Structures, Braunschweig Institute of Technology, Hermann-Blenk-Str. 35, 38108 Braunschweig, Germany

ARTICLE INFO

Article history:
Received 13 March 2017
Received in revised form 10 July 2017
Accepted 13 August 2017
Available online xxxx

Keywords:
Asymmetric sandwich
Debond
Double cantilever beam
Plasticity
Elastic-plastic beam theory

ABSTRACT

This paper analyzes the delamination behavior of thin-walled asymmetric sandwich beams. DCB tests are used for the calculation of fracture toughness values and show a high dependency of the delamination behavior on the damage configuration and geometry. The thickness of the sandwich skin and the position of the delamination relative to the adhesive layer prove to be crucial. The skin's plastic deformation is quantified by estimation using graphical and semi-analytical methods. Plastic strains occur over most of the cross section of the delaminated bending aluminum skin and have significant effects on the resulting fracture toughness. All results underlie significant variances due to several influences as shown.

1. Introduction

Due to snowball effects the reduction of structural mass of transport aircraft can lead to major increases of their efficiency [1]. Modern aircraft configurations widely use carbon-fiber-reinforced polymers (CFRP) because of their high specific stiffness and strength to achieve lighter masses and better load bearing capacities [2]. Stability-driven problems are a challenging topic connected to fiber-reinforced polymers (FRP) that can lead to interlaminar delaminations within the FRP. Regarding this, current designs usually cannot exploit the whole potential of the modern materials since the number of stiffeners and the thickness of FRP-skins often may not be reduced [3]. One possible approach to overcome these limitations are sandwich structures. In general, they are made of two thin but stiff skins and a lightweight core supporting the skins. Their outstanding bending stiffness is able to increase the structure's global resistance against stability failure and the elastic foundation of the skins by the core reduces local skin buckling. Hence, frame and stringer pitches can be increased leading to potential mass reductions [4].

This work analyzes an asymmetric sandwich concept for transport aircraft fuselages proposed by the German Aerospace Center (DLR, see Fig. 1) [5]. It is made of an inner CFRP skin, a PMI-foam core and a thin outer aluminum skin. Besides the general advantage of sandwich structures regarding bending stiffness this set-up provides further benefits by an integration of functions of the single components. The CFRP face layer carries the main loads, whereas both core and aluminum protect

* Corresponding author at: Inst. of Aircraft Design and Lightweight Structures, Technische Universität Braunschweig, Hermann-Blenk-Str. 35, 38108 Braunschweig, Germany.

E-mail address: m.pietrek@tu-braunschweig.de (M. Pietrek).

http://dx.doi.org/10.1016/j.engfracmech.2017.08.025
0013-7944/

Please cite this article in press as: Pietrek M, Horst P. Determination of the fracture toughness of debonded asymmetric sandwich beams with a thin-walled skin considering plastic deformation. Engng Fract Mech (2017), http://dx.doi.org/10.1016/j.engfracmech.2017.08.025

Nomenclature

a	delamination length
Δa	propagation of delamination length
b	width of DCB specimen and width of beam (equivalent)
CO	coordinate origin
EI_{eq}	equivalent stiffness: product of Young's Modulus E and second moment of area I
F	load on DCB specimen
F_{Ic}	critical load for mode I propagation of delamination progress
G_{Ic}	fracture toughness for mode I delamination
G_c	general fracture toughness
h	half height of beam
i	count variable
M	bending moment
$\boldsymbol{N}$	vector of beam cross sectional reaction force
N_x	beam cross sectional reaction force in x-direction
p	fitting parameter for analytical expression of stress-strain-curve
p^*	fitting parameter for analytical expression of stress-strain-curve
r	fitting parameter for analytical expression of stress-strain-curve
r_2	fitting parameter for analytical expression of stress-strain-curve
r^*	fitting parameter for analytical expression of stress-strain-curve
s	moving coordinate of force/lengthening of beam section
ΔU	energy dissipated during delamination propagation
ΔU_{total}	total energy dissipated during delamination propagation
ΔU_{delam}	energy dissipated by opening of delamination
$\Delta U_{plastic}$	energy dissipated by plastic deformation
W	applied work during beam deflection
W_e	work transformed into elastic deformation of beam
W_p	work transformed into plastic deformation of beam
x	Cartesian coordinate in beam longitudinal direction
z	Cartesian coordinate in beam thickness direction
z_p	half height of elastic area in center of beam cross section
δ	load point displacement
Δ	virtual increase of the crack length a to account for specimen rotation during testing
ε	strain
ε_{max}	strain in outer fiber of beam
ε_n	normalized strain ($=\varepsilon/\varepsilon_{0,2}$)
ε_{nu}	normalized ultimate strain ($=\varepsilon_u/\varepsilon_{0,2}$)
ε_u	ultimate strain
$\varepsilon_{0,2}$	yield strain
σ	stress
σ_{max}	stress in outer fiber of beam
σ_e	elastic stress
σ_n	normalized stress ($=\sigma/\sigma_{0,2}$)
σ_p	plastic stress
$\sigma_{0,2}$	yield stress

the inner skin from impacts and serve as thermal and acoustic insulation. Furthermore, the aluminum skin acts as impact detection layer, lightning protection and provides electromagnetic compatibility.

A major challenge in the application of sandwich structures are the detection of damages and the understanding of their damage tolerance behavior. Especially smaller defects such as impacts, indentations, wrinkling and skin delaminations are rather difficult to localize but can lead to undesirable failure behavior [6]. While some effort has been made to analyze the delamination behavior of symmetric sandwich structures (e.g. [7–12]) asymmetric sandwich configurations have not been studied extensively, yet. Carlsson et al. [6] present an analytical approach for the calculation of two-dimensional energy release rates (ERR) of asymmetric sandwich beams based on the J-integral and work of Kardomateas et al. [13].

A previous publication [14] shows the delamination behavior of asymmetric sandwich shells with very thin aluminum skins under axial compressive loads and attempts to predict the failure loads by stress- and strain-based failure criteria. As shown, these are not suitable to correctly predict the failure loads. Furthermore, it is recognized, that plastic deformation of the thin-walled aluminum skin dissipates deformation energy and therefore probably influences the delamination process and limits the capability of the simulation model. Avilés et. al. show that mode I is dominating laminar (i.e. bidirectional)