Engineering Fracture Mechanics 76 (2009) 594–613

Contents lists available at ScienceDirect

Engineering Fracture Mechanics

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

# On the analysis of a mixed mode bending sandwich specimen for debond fracture characterization

A. Quispitupa [a], C. Berggreen [a,*], L.A. Carlsson [b]

[a] Department of Mechanical Engineering, Technical University of Denmark, Nils Koppels Allé, Building 403, DK-2800 Kgs. Lyngby, Denmark
[b] Department of Mechanical Engineering, Florida Atlantic University, 777 Glades Road, Boca Raton, FL 33431, USA

ARTICLE INFO

*Article history:*
Received 17 June 2008
Received in revised form 13 November 2008
Accepted 4 December 2008
Available online 24 December 2008

*Keywords:*
Debond failure mode
Sandwich structures
Mixed mode bending
Finite element analysis
Experimental mechanics

ABSTRACT

The mixed mode bending specimen originally developed for mixed mode delamination fracture characterization of unidirectional composites has been extended to the study of debond propagation in foam cored sandwich specimens. The compliance and strain energy release rate expressions for the mixed mode bending sandwich specimen are derived based on a superposition analysis of solutions for the double cantilever beam and cracked sandwich beam specimens by applying a proper kinematic relationship for the specimen deformation combined with the loading provided by the test rig. This analysis provides also expressions for the global mode mixities. An extensive parametric analysis to improve the understanding of the influence of loading conditions, specimen geometry and mechanical properties of the face and core materials has been performed using the derived expressions and finite element analysis. The mixed mode bending compliance and energy release rate predictions were in good agreement with finite element results. Furthermore, the numerical crack surface displacement extrapolation method implemented in finite element analysis was applied to determine the local mode mixity at the tip of the debond.


## 1. Introduction

Sandwich constructions are often utilized in wind turbine blades, naval and aerospace structures. Debonds between the face and core have a detrimental effect on sandwich structures since the load transfer between face and core is compromised. In the worst case scenario a debond could grow unstably with the risk of catastrophic failure of the structure. Debonds and other interfacial flaws may be introduced during manufacturing and they might grow under both static and cyclic loading during the service lifetime of the structure [1–3]. The different isotropic and orthotropic constituents of widely different material properties render the analysis of this interfacial failure mode quite complex.

Due to the bimaterial character of the face/core interface in a sandwich, the analysis of fracture must recognize the mixed mode loading and that the fracture toughness depends on the relative amount of mode I and mode II at the debond tip [4–6]. Hence, it is important to develop reliable and efficient tests methods which enable accurate measurements of the mixed mode debond toughness.

The primary objective of this paper is to establish a test principle for the study of propagation of face/core debonds under static mixed mode loading. Subsequently, the test principle will be extended to the study of crack growth during cyclic loading. Hence, it is desirable that the local mode mixity does not strongly depend on crack length.

Several tests methods have been proposed during the last two decades for static debond fracture characterization of sandwich composites. Specimens such the cracked sandwich beam (CSB) [7], double cantilever sandwich beam (DCB) [8], tilted

* Corresponding author. Tel.: +45 4525 1373; fax: +45 4588 4325.
*E-mail address:* cbe@mek.dtu.dk (C. Berggreen).

0013-7944/$ - see front matter Crown Copyright © 2008 Published by Elsevier Ltd. All rights reserved.
doi:10.1016/j.engfracmech.2008.12.008

**Nomenclature**

| | |
|---|---|
| $a$ | crack length |
| $b$ | width of the specimen |
| $c$ | lever arm distance |
| $c_m$ | stiffness parameters of the materials above and below the interface crack |
| $h$ | characteristic distance to calculate the mode mixity at the crack tip |
| $h_c$ | core thickness |
| $h_f$ | face sheet thickness |
| $k$ | shear correction factor |
| $x$ | short distance behind the crack tip |
| $A$ | extensional stiffness for a sandwich case |
| $B$ | coupling stiffness for a sandwich case |
| $C_{\text{CSB}}$ | compliance of the cracked sandwich beam |
| $C_{\text{DCB\_lower}}$ | compliance of the lower sub-beam of the double cantilever beam |
| $C_{\text{DCB\_upper}}$ | compliance of the upper sub-beam of the double cantilever beam |
| $C_{\text{DCB}}$ | $C_{\text{DCB\_upper}} + C_{\text{DCB\_lower}}$ total compliance of the double cantilever beam |
| $C_{\text{MMB}}$ | compliance of the mixed mode bending sandwich specimen |
| $D$ | bending stiffness for a sandwich case |
| $D_1$ | $E_f h_f^3/12$ (upper sub-beam at the debonded region) |
| $D_2$ | $D - B^2/A$ (lower sub-beam at the debonded region of the sandwich specimen) |
| $D_{\text{debonded}}$ | effective flexural stiffness of the debonded region of the cracked sandwich beam |
| $D_{\text{intact}}$ | flexural stiffness of the intact region of the cracked sandwich beam |
| $E_c$ | elastic modulus of the core |
| $E_f$ | elastic modulus of the face sheet |
| $G$ | energy release rate calculated from finite element analysis |
| $G_{\text{CSB}}$ | energy release rate of the cracked sandwich beam |
| $G_{\text{DCB}}$ | energy release rate of the double cantilever beam |
| $G_f$ | shear modulus of the face sheet |
| $G_{\text{MMB}}$ | energy release rate of the mixed mode bending sandwich specimen |
| $G_m$ | shear modulus of the materials at the interface crack |
| $G_{xz}$ | shear modulus of the core |
| $G_{\text{II}}/G_{\text{I}}$ | global mixed mode ratio |
| $K$ | elastic foundation modulus |
| $2L$ | span length |
| $P$ | load applied to the mixed mode bending specimen at a distance $c$ |
| $P_{\text{I}}$ | mode I load |
| $P_{\text{II}}$ | mode II load |
| $P_R$ | reaction load at the right support of the mixed mode bending specimen |
| $\alpha$ | parameter to partition the reaction load at the left support |
| $\beta$ | parameter to partition the reaction load at the left support, equal to $1 - \alpha$ |
| $\beta$ | Dundur's parameter |
| $\varepsilon$ | oscillatory index at the crack tip |
| $\eta$ | parameter for the elastic foundation modulus |
| $\psi$ | mode mixity at the crack tip |
| $\delta_c$ | displacement of the central part of the mixed mode bending sandwich specimen |
| $\delta_{\text{CSB}}$ | displacement of the cracked sandwich beam |
| $\delta_{\text{DCB\_lower}}$ | displacement of the lower sub-beam of the double cantilever beam |
| $\delta_{\text{DCB\_upper}}$ | displacement of the upper sub-beam of the double cantilever beam |
| $\delta_{\text{DCB}}$ | $\delta_{\text{DCB\_upper}} + \delta_{\text{DCB\_lower}}$ total displacement of the double cantilever beam |
| $\delta_{\text{MMB}}$ | displacement of the mixed mode bending sandwich specimen |
| $\delta_x$ | shear relative displacement of the crack flanks |
| $\delta_y$ | opening relative displacement of the crack flanks |
| $\Delta$ | displacement of the mixed mode bending specimen loaded by $P_{\text{I}}$ |
| $\upsilon_m$ | Poisson's ratio |

sandwich debond specimen (TSD) [9], three-point sandwich beam (TPSB) [10], single cantilever sandwich specimen (SCS), end-loaded sandwich specimen (ELSS) and the DCB subjected to uneven bending moment named DCB-UBM [11] were proposed (Fig. 1). All sandwich specimens have an artificial debond at the face/core interface. Furthermore, for all specimens, except the DCB-UBM (with fixed mode mixity), the mode mixity changes as the debond length changes.