Accepted Manuscript

Investigation of failure initiation in curved composite laminates using a higher-order beam model

C. Thurnherr, R.M.J. Groh, P. Ermanni, P.M. Weaver

PII: S0263-8223(16)32849-5
DOI: http://dx.doi.org/10.1016/j.compstruct.2017.02.010
Reference: COST 8229

To appear in: *Composite Structures*

Received Date: 12 December 2016
Accepted Date: 2 February 2017

Please cite this article as: Thurnherr, C., Groh, R.M.J., Ermanni, P., Weaver, P.M., Investigation of failure initiation in curved composite laminates using a higher-order beam model, *Composite Structures* (2017), doi: http://dx.doi.org/10.1016/j.compstruct.2017.02.010

Investigation of failure initiation in curved composite laminates using a higher-order beam model

C. Thurnherr[a,*], R.M.J. Groh[b,*], P. Ermanni[a], P.M. Weaver[b]

[a]Laboratory of Composite Materials and Adaptive Structures, Department of Mechanical and Process Engineering, ETH Zürich, Tannenstr. 3, CH-8092 Zürich, Switzerland
[b]Advanced Composites Centre for Innovation and Science, University of Bristol, Queen's Building, University Walk, Bristol, BS8 1TR, UK

Abstract

Curved laminates are prone to delamination failure from applied bending moments that straighten out the laminate and induce tensile stresses in the unreinforced radial direction. These non-classical through-thickness stresses are important even for thinner configurations and need to be accounted for in the design of lightweight composite structures, preferably in a computationally efficient manner. Here, we investigate failure-inducing critical stresses for a number of curved laminates using a higher-order beam model derived from the Hellinger-Reissner mixed variational principle, which guarantees that the hoop, interlaminar shear and radial stresses are equilibrated. By solving the governing equations of the theory in the strong form using the pseudo-spectral differential quadrature method, the model is capable of predicting accurate 3D stress fields in curved laminates, even in the vicinity of localised features such as supported edges. The model is used alongside commonly used failure criteria to reproduce experimental failure initiation results found in the literature, and the comparison suggests that failure mode, location and load are all predicted accurately. Finally, failure maps that highlight the critical stress component for failure initiation are constructed. As the thickness of the curved laminate increases, the critical stress component transitions from intralaminar hoop stress to interlaminar shear or radial stress depending on the specific laminate configuration. These findings and failure maps collectively provide insights into the mechanics of failure initiation that should also prove useful for design purposes.

Keywords: Curved laminates, higher-order modeling, interlaminar stresses, anisotropic materials, damage onset

1. Introduction

Due to their high specific strength and stiffness the predominance of composite materials in primary load-bearing aircraft structures is on the rise. In curved laminates, such as T-shaped stringers on aircraft wings, interlaminar stresses arise even for thin wall-thicknesses when the curved geometry is straightened and these interlaminar stresses are known drivers of delamination onset [1, 2]. To account for delamination failure as early as possible in the design process, analytical tools that accurately predict the stress fields in a computationally efficient manner are key [3, 4, 5].

To date, the investigation of failure initiation and certification of load-bearing aircraft structures requires detailed experimental validation from the coupon to the assembly level. Hence, examples of experimental studies on failure initiation in curved laminates are plentiful. Wimmer et al. [6] studied the failure initiation and propagation in L-shaped laminates experimentally and numerically. Hao et al. [7] conducted experiments to investigate delamination in different laminates. Michel et al. [8] analyzed curved laminates in four-point bending tests. Sun et al. [9] investigated failure loads and modes in thick L-shaped laminates with different lay-ups. Although, experimental studies are limited to specific geometries, boundary conditions and lay-ups, they are essential in validating numerical models used throughout the design process. In the present paper we use the experimental results of Sun et al. [9] as a reference to compare our simulation results, with the ultimate goal of predicting accurate failure loads, modes and locations in curved laminates.

Most et al. [3] highlighted the importance of accurately quantifying the stress distribution when analysing debonding failure in thick curved laminates, and various methods have been suggested in the literature to cal-

*Corresponding author
Email address: thclaudi@ethz.ch (C. Thurnherr)