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Progressive Damage Analysis for Aerospace Composite Structures Subjected to Impact Loads

By

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by

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Abstract

Advanced fibre-reinforced composite laminates are increasingly utilized in civil aircraft structures due to their high stiffness and strength-to-weight ratio. Carbon Fibre-Reinforced Polymers (CFRP) materials possess excellent in-plane mechanical characteristics but exhibit relatively high brittleness through the thickness. Consequently, internal damage such as fibre breakage, matrix-cracking, resin plastic deformation, and interlaminar delamination are commonly observed in layered composite structures subjected to out-of-plane impact loads. Identifying damage-tolerant designs in laminated composite materials subjected to low-velocity (LVI) or high-velocity impact (HVI) by foreign objects is challenging and complex to evaluate during the early design stages of new composite airframe structures.
The complexity arises from the numerous parameters defining laminate configurations (e.g., material properties, layup configuration, ply thickness, and fibre architecture) and impact scenarios (e.g., impactor geometry, material, mass, energy, or velocity). Conducting physical tests for every possible configuration during the design phase is time-consuming and prohibitively expensive. In addition, numerical and analytical methods are not fully reliable in predicting failure, durability, or damage propagation in fully assembled composite structures. As a result, extensive laboratory testing is still required to certify the performance and impact behaviour of laminated composite structures.
This study aims to develop a robust and efficient simulation methodology for predicting damage and energy absorption in composite structures under various dynamic loads, focusing on two selected material architectures: layered unidirectional and triaxial-braided composites.

This research builds on existing literature by introducing a high-fidelity meso-scale modelling framework that emphasizes both intralaminar and interlaminar mechanical behaviours in selected material fibre-architectures. The objective is to establish physics-based guidelines for defining numerical model parameters based on constitutive experimental properties, thereby minimizing the need for extensive calibration and correlation phase. A series of closed-form expressions, derived from evaluated material mechanical properties and fibre-architectures, are introduced to define Finite Element Analysis (FEA) numerical fracture initiation and propagation parameters, which are crucial for the selected material structures under varying impact loads.
The developed methodology includes innovative numerical techniques to characterize the elastic

response and post-failure fracture mechanics evolution of selected composite materials. Constitutive intralaminar and interlaminar fracture mechanisms observed in the chosen material architectures are analysed and modelled separately using structured cohesive interface elements. A series of intralaminar single-element numerical analyses and fracture toughness mechanical specimen models are provided to investigate and characterize damage nucleation and evolution across the selected material structures. A set of literature benchmark analyses is included to verify the developed numerical modelling framework. A fibre-aligned shell-cohesive modelling approach is introduced to replicate the mechanical behaviour of layered unidirectional composites under various loading conditions. Conversely, a solid-cohesive meso-scale modelling technique is presented for analysing the intertwined fibre architecture characteristic of textile triaxial-braided composites. A series of MATLAB tools are proposed to automatically reconstruct the designed meso-scale mesh topology based on selected mesh sizes and composite panel geometries.

An extensive experimental study is conducted to assess the low-velocity and high-velocity impact performance of selected composite material architectures. The study specifically addresses material sensitivity to Barely Visible Impact Damages (BVID) and ballistic impact loads with velocities ranging from 5 m/s to 450 m/s. A detailed analysis of contact force evolution and residual damage morphology through post-mortem panel analysis and X-ray CT-scans is provided to validate the developed numerical model results. A scientific photogrammetry environment is designed to capture 3D high-speed displacement and deformation fields of the back-face panel when impacted by a high-velocity axial-symmetric metallic projectiles. The investigated material architectures are compared under selected dynamic loads to evaluate their overall impact performance and assess their damage tolerance mechanical properties.

This research advances the understanding of impact behaviour in composite structures by offering a robust simulation methodology that reduces reliance on experimental calibration and correlation techniques. A close overlook of fracture mechanisms and damage tolerant mechanical properties for selected material architectures is provided and compared with the computed numerical solutions. The findings significantly advance the development of progressive damage numerical models, offering valuable insights for virtual testing and supporting the building block certification process used in aerospace engineering design.

Publications

Journal paper publications and conference proceedings arising from this thesis include:

- A. Polla, P. Piana, E. Cestino, and G. Frulla. Delamination and fracture modeling techniques for shell composite structures in LS-DYNA. *13th European LS-DYNA Conference*, page 12, 2021.

- A. Polla, G. Frulla, E. Cestino, R. Das, P. Marzocca. Numerical and experimental structural characterization of composite advanced joint for ultra-light aerospace platform. *In Proceedings of the 33rd ICAS Congress*, Stockholm, Sweden, pages 4–9, 2022.
- C. Patuelli, A. Polla, E. Cestino, and G. Frulla. Experimental and numerical dynamic behavior of bending-torsion coupled box-beam. *Journal of Vibration Engineering & Technologies*, 11(7):3451–3463, 2023.
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