

MULTI-STAGE FINITE ELEMENT ANALYSIS OF IMPACT AND FATIGUE-INDUCED DAMAGE ACCUMULATION IN ROTOR BLADE COMPOSITE SPARS FOR NEXT GENERATION HELICOPTERS

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ABSTRACT

This study presents a high-fidelity finite element framework using ANSYS 2025 R1 to analyze progressive damage in carbon fiber-reinforced polymer (CFRP) helicopter rotor blade spars under combined impact and fatigue loading. A detailed three-dimensional laminated model incorporates anisotropic elasticity, ply orientations, and delamination behavior. Hashin and Tsai–Wu failure criteria were applied to capture multiple damage modes, while Explicit Dynamics simulated high-velocity impact events including delamination and energy dissipation. Post-impact fatigue degradation was assessed using Stress–Life (S–N curve) data, revealing significant reductions in service life due to localized damage accumulation. Sub-modelling of ply-drop regions improved prediction of stress concentrations and crack initiation. Results confirm that impact-induced defects accelerate fatigue-driven stiffness loss, underscoring the need for integrated modelling approaches in rotor blade design.

Keywords: ANSYS Simulation, CFRP, Composite Rotor Blade Spars, Explicit Dynamics, Fatigue Life Prediction, Impact Analysis

1. INTRODUCTION

The structural integrity of helicopter rotor blade spars is critical for ensuring flight safety under severe conditions such as high-velocity impacts and cyclic fatigue. Carbon fiber-reinforced polymers (CFRPs), favoured for their high strength and stiffness, remain vulnerable to barely visible impact damage (BVID) from bird strikes or foreign object damage (FOD), which can significantly reduce fatigue life during service.

1.1 Overview of previous work

Hofman et al. [1] proposed a fatigue-CZM model enhanced with XFEM for high-cycle fatigue in composite laminates, accurately predicting matrix cracking and delamination with reduced mesh sensitivity and computational cost. Cheng et al. [2] developed a coupled PDM framework integrating pre-fatigue, low-velocity impact (LVI), and fatigue for helicopter tail structures, validated against experimental data with ~5% error, demonstrating a ~40% fatigue life reduction due to LVI damage. Ju Qiu [3] improved dent-depth vs. impact-energy relations for LVI in laminates, showing that conventional bilinear models underestimate damage beyond threshold energy. Boudounit et al. [4] applied Hashin criteria in Abaqus for GRP wind blades under LVI, revealing trailing-edge damage concentration and confirming velocity as the main damage driver. Guorui Yu et al. [5] simulated ballistic impacts on rotor blades using explicit dynamics with Hashin element deletion, capturing complete failure progression, and achieving <10% deviation from tests. Hadar et al. [6] used ANSYS ACP with Solid186/187 elements to model composite tail rotor blades, highlighting the importance of mesh refinement and ply orientation in stress prediction. Pao et al. [7] demonstrated synergistic CFD–PDM coupling to capture progressive crack density and stiffness loss (~8%) in CFRP D spars. Parkhe et al. [8] analysed dynamic stress in rotating CFRP blades, identifying a 15% stress rise in damaged blades and predicting rupture after 1.2 times service life. Elumalai et al. [9] compared conventional and integrated wing spars under bird strike, showing 67% lower energy absorption in optimized designs, enhancing impact resilience. Liu et al. [10] examined adhesive joint failures via sub-modelling, reporting ≥50% fatigue life reduction due to interfacial stress peaks, underscoring the need for local refinement at ply-drop regions.