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Progressive failure analysis for thin-walled composite beams under fatigue loads

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ABSTRACT

A thin-walled beam (TWB) model for integrated progressive failure analysis in composite materials under fatigue loading is presented for the first time. The model is computationally lean and capable of tracking the spatial distribution and further propagation of fatigue-induced damage in beam-like thin-walled composite structures (TWCS) by accounting for both sudden and gradual degradation of strength and stiffness moduli of material cells located at arbitrary positions. An integrated TWB model of a cylindrical symmetrical 8-layer test structure was studied to obtain insights into damage progression patterns and interactions between different damage mechanisms. It was shown that it is possible to localize and quantify the extent of damage at individual layers while providing explanations for damage initiation and propagation in engineering terms. The proposed model provides a computationally efficient platform for performing fatigue-induced progressive failure analysis in TWCS such as rotating blades of wind turbines or helicopters, allowing the assessment of a number of *what-if* scenarios with current off-the-shelve computing power.

1. Introduction

Thin-walled composite structures (TWCS) are nowadays widely used in critical applications including aerospace, mechanical and civil engineering, due to their high strength/weight ratio, advanced mechanical capabilities and the versatility to suit application-specific designs [1–3]. On the downside, although it is generally accepted that composites are tougher than metals, thus capable of better arresting the growth of initial defects, their size and occurrence in composite materials is far greater than in metals [4,5] given the high variability of current manufacturing processes. Among other reasons this leads to a higher uncertainty in the analysis of the fatigue and failure behavior of composites compared to metals [6]. These arguments provide a strong motivation for studying fatigue-induced damage in composites and its propagation mechanisms, particularly for structures withstanding a complex stress state throughout a high number of cycles. This condition occurs in rotating machinery such as wind turbine or helicopter rotors [7], often modeled as TWCS, where stringent fatigue conditions can threat the sturdiest materials and pose significant modeling challenges even under constant-amplitude and -direction excitation. While damage in metals is often quantified by the increasing size of an initial crack, fatigue damage in composite materials progresses in a more spread-out and nonlinear way involving a number of failure mechanisms such as matrix cracking, fiber breakage, de-bonding, delamination and interface cracking, as well as complex interactions among them [6,8,9].

Macroscopically speaking, fatigue-induced damage in composites can manifest in two fundamentally different ways [10]: (1) by *gradual degradation of material properties*, slowly progressing through the structure by accumulating partial damage from different failure modes, leading to a continuous reduction in both strength and stiffness moduli, or (2) by *sudden failure*, occurring when the instantaneous material stress exceeds corresponding strength moduli, considering the gradual degradation of the latter. In wind turbine rotor blades, for example, stiffness reduction can lead to increased flapwise oscillations under turbulent wind load, possibly violating minimum clearance requirements and having detrimental effects on the blade's local wind flow and hence its aerodynamic performance [11,12]. On the other hand, the unnoticed strength reduction accumulated over time can lead to a catastrophic failure under extreme load conditions, such as the passage of a hurricane or tropical storm [12,13]. In either case, it is important for the designer to be able to anticipate accumulated fatigue

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damage over the lifetime of the rotating structure and specify recommended repair or replacement activities.

Naturally, expected fatigue damage is routinely assessed in the design phase of rotating machinery [14]; a description for a typical procedure for the case of wind turbine rotors is given in [12]. Given the complexity of the load and stress histories, several restricting assumptions are generally made, such as bending about one axis only and the use of the Palmgren-Miner's rule [15] for cumulative damage assessment. In this framework, it is difficult or impossible to consider the progressive degradation of the mechanical properties of the blade materials (i.e. strength and stiffness), let alone the spatial extent and propagation of the damage/degradation area. In order to address some of these issues, Shokrieh and Rafiee [16] proposed a progressive fatigue damage model which incorporates both a *gradual* reduction of the stiffness and strength moduli as a consequence of materials degradation due to fatigue as well as conditions for *sudden* failure, and applied it to the assessment of fatigue life of a wind turbine blade. However, only global (i.e. whole structure) fatigue lifetime values were shown, without resolving the spatial damage distribution.

Spatial tracking of damage in composite materials has been studied by several groups in recent years, with the focus being on progressive failure analysis of simple geometries (i.e. sample coupons) subject to either static or fatigue loads. Chen et al. [17] studied the progression of damage caused by static loads in a through hole-loaded composite sample combining damage assessment with a finite-element (FE) analysis implemented in ABAQUS®, allowing for the progressive degradation of the model's materials properties. Their analysis included both in-ply and delamination failure modes, where the latter tapped into ABAQUS' capability of modeling cohesive elements. A similar work was presented by Lee et al. [18], who conducted a progressive failure analysis for through hole-loaded composite samples and static loads, implementing an ABAQUS subroutine to iteratively modify the FE stiffness matrix as a consequence of materials degradation via the Puck failure criteria. Nishikov [19] followed a similar approach for investigating fatigue-induced damage in composites due to matrix cracks and delamination, providing damage maps qualitatively comparable to experiments. The commercial software suite GENOA/AlphaStar® works similarly as the approaches described in the last three references, combining commercial FE solvers such as ABAQUS, ANSYS® and NASTRAN®, among others, with proprietary damage progression tools.

Cárdenas et al. [20] conducted a static damage propagation analysis on numerical test case of a composite helicopter blade comparing the results of their home-built damage progression software, based on a Librescu-type [21] thin-walled beam (TWB) model and a failure progression algorithm, with those yielded by a shell-based FE model built in GENOA/ANSYS. Damage predictions in both models for monotonically increasing load displayed a strikingly similar damage topology at different load stages up to load values close to final failure, in spite of the restraining assumptions of the TWB formulation (i.e. undeformable cross-section, linear distribution of the shear strain, etc.) as well as the inevitable differences in the failure criteria formulation of the beam versus the shell model. Overall, the TWB's predicted evolution of the damage topology and volume lay within 10% deviation with respect to that observed in GENOA. On the other hand, the computational time required by the latter to yield a solution ranged in the order of hours (i.e. 10–30 h) while the former was of the order of minutes (i.e. 10–30 min). In a follow-up work, Cárdenas et al. [22] presented a dynamical version of their code allowing for damage propagation in wind turbine blades to be modeled under realistic loads (both stochastic, arising from the turbulent wind field, and deterministic). The load cases studied were chosen to assess damage from extreme stationary loads as the code was limited to static failure propagation at that time.

The present work proposes a novel TWB-based progressive failure propagation model for composite structures designed to assess fatigue-induced damage propagation in real-world composite structures such as wind turbine or helicopter blades. The relevance of a reduced-order TWB model, which allows retaining significant capabilities of more sophisticated formulations (i.e. shells) while reducing the mathematical description down to a few degrees of freedom, is that it provides a computationally efficient platform to perform the intensive and iterative calculations involved in damage tracking, while still being sufficiently accurate for most design purposes. The new method taps into the significant progress made in the recent past with the modeling of thin-walled structures [7,21,23] and progressive failure analysis [26,30], the capabilities of which have been already validated against shell-based FE models in the previous works by Cardenas et al. mentioned above [20,22], while drawing on powerful yet simple fatigue damage and degradation modeling tools for composites [9,10,25]. The proposed methodology opens the way to applications such as fatigue damage progression modeling of rotary machinery under realistic operating conditions (as opposed to studies of design cases only), with previously unattained computational efficiency.

The rest of the paper is organized as follows: Section 2 reviews the adopted TWB and fatigue models, and then describes the test structure for implementing the developed algorithms. Section 3 presents a comprehensive discussion of the results obtained, providing insights into the mechanisms in action for initiating and propagating fatigue-induced damage at both earlier and later stages of the load history, as well as explaining those mechanisms and the resulting spatial damage distribution in engineering terms. Finally, concluding remarks are given in Section 4.

2. Methodology

2.1. Thin-walled beam model

Reduced-order thin-walled beam (TWB) models offer the significant advantage of allowing for computationally efficient modeling of beam-like hollow structures while being capable of recovering detailed strain/stress information at the structure's shell which is comparable with more sophisticated formulations (i.e. shells). As stated by Zhang and Wang [24], the formulation put forward by Librescu and Song [21] appears to be the most detailed one for the modeling of thin-walled composite structures (TWCS). Although there are several other works in TWB modeling, some with more advance features in specific niches [27,28], the Librescu and Song's formulation can yield semi-analytical expressions for the stiffness tensor of arbitrary cross-sections, a useful feature when assessing damage-related loss of stiffness. For this reason, the latter framework was used in Cárdenas et al. [20] and Cárdenas et al. [22] for assessing damage progression.

While TWB models, and particularly those derived from the Librescu-Song framework, have been well documented in literature [21,23], for the purposes of a self-contained description of the present work it seems appropriate to provide a brief outline of the TWB component of the model introduced here. A TWB model reduces all the geometric and material information of the shell material down to a single axial line where the global displacement field (spanwise, flapwise, edgewise and rotational motion) is defined, very much like in a standard beam model. However, unlike the latter, the TWB model is capable of recovering strain and stress information at the shell material with some detail (3D), based on the knowledge of the global displacements alone. Reconstruction of the 3D information is based on the following conditions [21]: