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State of the art in fatigue modelling of composite wind turbine blades

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ABSTRACT

This paper provides a literature review of the most notable models relevant to the evaluation of the fatigue response of composite wind turbine blades. As wind turbines spread worldwide, ongoing research to maximize their lifetime – and particularly that of wind turbine blades – has increasingly popularized the use of composite materials, which boast attractive mechanical properties. The review first presents the wind turbine blade environment, before distributing fatigue models broadly between three categories: life-based failure criterion models, which are based on S-N curve formulations and constant-life diagrams to introduce failure criteria; residual property calculation models, which evaluate the gradual degradation of material properties; and progressive damage models, which model fatigue via the cycle-by-cycle growth of one or more damage parameters. These are then linked to current testing standards, databases, and experimental campaigns. Among the fatigue modelling approaches covered, progressive damage models appear to be the most promising tool, as they both quantify and qualify physical damage growth to a reasonable extent during fatigue. The lack of consensus and shortcomings of literature are also discussed, with abundant referencing.

1. Introduction

1.1. Background

The first wind turbine to generate electricity was a battery charging machine installed in July 1887 by Scottish academic James Blyth. Megawatt-scale power was subsequently first extracted from the Morgan-Smith wind turbine at Grandpa's Knob in Vermont, USA, in 1941. The turbine was equipped with sizable steel blades, of which one failed after a mere few hundred hours of intermittent operation.

Today, with the growing necessity to opt out of fossil fuel dependency in favour of renewable energies, wind turbines technologies are the focus of significant research and development efforts. During recent years, wind turbines have experienced a marked increase in their dimensions. Blades are further subjected to increased cyclic bending and torsion loads, which form one root cause of fatigue in wind turbine blades. In general, wind turbines should have an operational life of at least 20 years however, given the considerable investments required to install and operate large wind farms, accurate lifetime prediction methods for the turbine are required to ensure the durability of these turbines.

The attractive mechanical properties of composite materials justify their growing use in wind turbine applications, but also a plethora of other areas: automotive, aerospace, and more. The word *fatigue* is defined by the ASM [1] as the phenomenon leading to fracture under repeated or fluctuating stresses having a maximum value less than the ultimate static strength of the material. One of the first papers on fatigue was published by Wühler, a nineteenth century technologist in the German railroad system. Ever since, fatigue has been the subject of substantial research; yet we still cannot fully characterize it, especially mechanically or environmentally.

1.2. Objectives

Research undertaken so far in this field has mainly focused on static and dynamic fatigue loading of composite wind turbine blades. Among the great many models for fatigue response prediction that have been added to the literature, there are ostensible overlaps, voids, and ambiguities that must be addressed in order to identify the best course of action for research in this field. Experimental characterization of fatigue behaviour of composite materials is time consuming and expensive. Generalisation by extending and extrapolating of experimental results for composite laminates is not straightforward and sometimes impossible. That is why modelling fatigue life is an important axis of research and one that deserves reviewing today, given the plethora of failure criteria and models developed, some describing specific load cases and others offering a more general scope of application.

By considering the complexity of the fatigue failure of composite

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materials, the level of present knowledge and shortcomings of existing models, the necessity of development of more general models with fewer limitations can be induced [2], and especially the opportunities for research can be revealed. The main objective of this literature review is thus to compare and contrast some of the most important models and approaches developed in the last three decades to attempt in modelling the fatigue response of composite laminates.

This review aims to provide an overview of the current methods, in comparison to the other ones and most prominent theories, through a critical viewpoint, so as to be constructive and conclusive. Despite the fact that the fatigue behaviour of metals are already well-developed and validated, their "conventional" fatigue models may not be applied to composites due to their high anisotropic and heterogeneous behaviour. The underlying aim is to identify new paths for future improvements and shed light on the most ambiguous aspects of composite fatigue research, particularly in the evolving case of wind turbine applications.

2. Problem definition

2.1. Loading of wind turbine blades

Fatigue can have a direct or indirect effect on the overall performance of wind turbine blades, accelerating their degradation process and decreasing their energy production efficiency. According to Brondsted [3], fatigue relies on three design drivers of the blades; aerodynamic performance (blade shape), power performance (power efficiency, power curves, noise) and loading performance. Wind turbine blades and rotors are subjected to a high number of loading-unloading cycles, with highly stochastic loads (at times reaching extremes) during their baseline service life of 20 years. Mandell [4], and van Delft [5], have estimated that number to be around 10^8 to10^9 in a given life. Blade loads include deterministic, easily predictable components as well as non-deterministic components evaluated in a statistical or probabilistic fashion with physical considerations [6]. Wind turbine blade loads act in two orthogonal directions [2], *flapwise* and *edgewise* service load as seen in Fig. 1.

- *Flapwise load*: carried by main spar, due to wind action (aerodynamic loads) and acting perpendicularly on the rotor plane; loads present high variability in both amplitude and mean, thereby inducing high scatter in load history data.
- *Edgewise load*: carried by blade reinforcement, consisting of gravitational loads arising from the blade's weight, and torsional loads driving the turbine. This loading is more deterministic and changes direction twice during each revolution. The frequency distribution contains two peaks [6], corresponding respectively to the wind-loading-induced centripetal load and blade self-weight gravitational load.

The above loading environment results from the distinctive structural characteristics of wind turbine blades compared to other common composite structures (such as those found in aerospace and automotive applications). The thickness of a wind turbine blade is the result of a trade-off between the ideal slenderness for aerodynamic efficiency and ideal thickness for structural integrity. As loading and stresses increase toward the rotor hub, wind turbine blades tend to increase in thickness toward the center of rotation (i.e. at the blade root), and gain in slenderness toward the tips. Wind turbine blades can be considered slender bodies and as such, their slenderness favours a uniaxial stress profile on the blade cross section. It must be also noted that both flapwise and edgewise loadings produce shear and torsional loads that contribute to the effects of blade fatigue over time. While this shear component is not always thoroughly accounted for in some of the more simplified fatigue models we shall explore, new algorithms and approaches more accurately account for such effects, as we shall see.

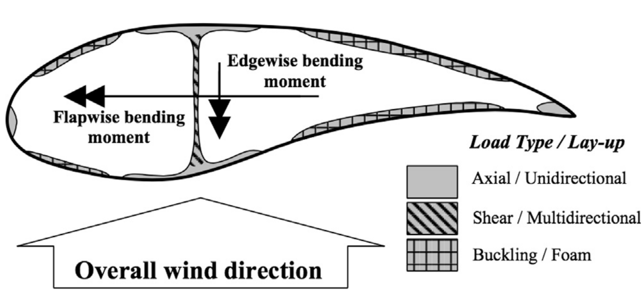

Fig. 1. Wind turbine blade cross-section and load plane definition [2].

As wind turbines increase in size, the edgewise fatigue loading becomes increasingly relevant for life prediction, as shown by Kensche [7]. In addition, the torsional eigenfrequency drops, with a risk that it may couple with lower bending modes, with disastrous consequences. Toward the trailing and leading edge of the blade structure, gravity increasingly dominates the stress and strains applied to the load-bearing structure in the rotor plane. An alternating, cyclic stress emerges as a result, with mean stress almost null. Furthermore, rapid change in wind direction known as gusting can be hazardous especially if the natural frequency of the wind gusting coincides with the turbine structure [8]. Wind shear, also referred to as wind gradient and described as the variation of wind velocity with height (or horizontal distance), can exacerbate the effects of gusting.

Small scale wind turbines are also widely present on the market for diverse applications. They share common features with the large scale ones in terms of structural design. Nevertheless, as their surface exposure is decreased, they are less exposed to environmental hazards and load variation generated by wind-loading-induced shear surface and gravity [3]. Furthermore, rotational speed (centrifugal stresses) and gyroscopic loads are higher in comparison to large wind turbine blades, implying higher fatigue cycles.

The impact of load variability and turbulence on fatigue life should be highlighted. Riziotis et al. [9] performed numerical modelling of wind and wind turbines of the 0.5 MW class and identified turbulence intensity to bear the most significant impact on fatigue load contributions, and therefore fatigue life of the turbine blade. Further, according to Mouzakis [10], terrain complexity surrounding the wind turbine could account for about 30% of additional fatigue loading contribution, including cyclic bending loads. According to Lange [11], the way loading history data is modelled strongly affects fatigue modelling reliability. A great number of complex, non-linear and irregular environmental factors specific to a given wind turbine's location therefore seemingly come in play when it comes to decomposing fatigue loading contributions on the particular wind turbine blades. An effect that can be advantageous to reduce the mean blade loading is called coning. It is the bending of the rotor blades in high winds that introduces centrifugal force loads which acts against the aerodynamic steady thrust loads however the coning effect can cause oscillations. Transient loads at start-up and shut-down of the turbine may lead to fatigue damage.

2.2. Material selection

2.2.1. Choice of fibres

Composite stiffness is largely dependent on the stiffness of its fibres and their volume fraction. So far, the most commonly used fibres have been the affordable glass fibres, although there is a clear growing tendency towards incorporating carbon fibres.

Most often, E-glass (i.e. borosilicate glass) fibres are used as the main reinforcements in composites. Their main properties are summarized in Table 1. As the volume fraction of fibres increases in unidirectional composites, the stiffness, tensile, and compression strength increase proportionally. Nonetheless, at high fibre volume fraction (above 65% [12]), there may be resin-deprived areas, thereby reducing fatigue performance. Fig. 2 schematizes the relationship between fibre