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3D damage characterisation and the role of voids in the fatigue of wind turbine blade materials

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ABSTRACT

The fatigue mechanisms of Glass Fibre Reinforced Polymer (GFRP) used in wind turbine blades were examined using computed tomography (CT). Prior to mechanical testing, as-manufactured $[+45/-45/0]_{3,s}$ glass/epoxy specimens were CT scanned to provide 3-dimensional images of their internal microstructure, including voids. Voids were segmented and extracted, and individual characteristics and volumetric distributions were quantified. The coupons were then fatigue tested in uniaxial loading at $R = -1\%$ to 40% of the nominal tensile failure stress. Some tests were conducted to failure for correlation with the initial void analysis and to establish failure modes. Other tests were stopped at various life fractions and examined using CT to identify key damage mechanisms. These scans revealed transverse matrix cracking in the surface layer, occurring predominantly at free edges. These free-edge cracks then appeared to facilitate edge delamination at the $45/-45°$ interface. Propagation from sub-critical, surface ply damage to critical, inner ply damage was identified with either a $-45/0°$ delamination, or a $0°$ fibre tow failure allowing a crack to propagate into the specimen bulk. Final failure occurred in compression and was characterised by total delamination between all the $45/-45°$ plies. A quantitative void analysis, taken from the pre-test CT scans, was also performed and compared against the specimens' fatigue lives. This analysis, to the authors' knowledge the first of its kind, measured and plotted approximately 10,000 voids within the gauge length of each specimen. The global void measurement parameters and distributions showed no correlation with fatigue life. A local ply-level investigation revealed a significant correlation between the largest void and fatigue life in the region of the laminate associated with the crack propagation from sub-critical to critical damage.

1. Introduction

The more widespread use of wind turbines and their increased capability represent important ways of meeting the growing worldwide energy demand. For increased power generation and a greater efficiency, the general trend is for larger turbines with an increased rotor diameter. Individual blade lengths in production are currently approach 60 m; a threefold increase in the past two decades [1]. The emergence of larger blades has resulted in an absence of corresponding long-term in-service data. With expected lifetimes of 20 years, and longer desired, the long-term integrity of the blade material has thus become an important area for research. As a result, extensive fatigue databases for wind turbine composites have been recently compiled [2,3], however non-transferability of results between different materials and load conditions still demands a large experimental effort for each new blade design and material used. A greater understanding of the fatigue damage modes and their accumulation is required to enable more accurate and predictive damage modelling. In addition to this, further insight into certain microstructural features, notably voids, is required, as their role in fatigue damage propagation remains uncertain. In order to achieve this mechanistic understanding, suitable experimental techniques are needed for observation and analysis. Micro-computed tomography (μCT) has been used to this end in the current work, as it allows 3-dimensional volumetric imaging of the whole material. Three tasks were identified in order to enable a complete, detailed understanding of fatigue damage in this material using μCT: firstly, to study the microstructure of the as-manufactured material including fibre tows, resin rich regions and voids; secondly, to perform a quantitative investigation into the material's void population including its affect on fatigue performance and, finally, to gain a mechanistic knowledge of the material's fatigue damage accumulation from initiation to failure.

2. Literature

Composites are known to exhibit four main fatigue damage mechanisms; fibre failure, fibre/matrix debonding, matrix

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cracking, and delamination [4]. For compressive or fully reversed loading, microbuckling of the 0° plies is also observed [5]. It has been found that the different mechanisms can dominate material degradation at different stress levels. At low load levels, matrix cracking is the predominant mechanism, at medium loads a combination of matrix cracking and delamination is observed, while at high loads fibre failure occurs [4]. The low load, high cycle fatigue nature of the wind turbine thus promotes matrix cracking. Matrix cracking is a widely investigated phenomenon, however most studies concern cross-ply laminates, and thus transverse (90°) matrix cracking [6,7]. These cracks have been noted to grow across the specimen width from the free edge, with their growth rate dependent on ply thickness and crack spacing rather than their own length [8,9].

Tong et al. [10] investigated crack development in $[0/90/-45/+45]_s$ glass fibre–epoxy composite in static tension and tension–tension (T–T) fatigue. Transverse cracking appeared first, followed by −45° cracks from the edges of existing 90° cracks, and finally +45° matrix cracks. Masters and Reifsnider [11] studied the fatigue crack growth of quasi-isotropic laminates, confirming the presence of 90° ply cracks that spread to form cracks in the neighbouring off-axis plies. In this study two different lay-ups were considered, $[0/90/\pm45]_s$ and $[0/\pm45/90]_s$. Each displayed distinctly different crack saturation patterns, despite initial damage of the transverse plies in both. This highlights the dependence on laminate lay-up for damage evolution. Gamby et al. [12] examined the development of cracks from free edges in laminates containing 0° and ±45° plies. It was found that the matrix cracks propagated from the free edges of the off-axis plies, and, as with the transverse cracks previously mentioned [8,9], were found to have a density based on distance from the free edge and the number of cycles.

Matrix cracking alone does not directly cause fatigue failure, however it is often a precursor to more critical mechanisms. Matrix cracks are often found to be responsible for delamination onset, due to the local stress concentrations that occur when they propagate into contact with ply interfaces [13]. Delamination is also known to occur at the laminate edge where the interlaminar stresses are highest, due to the elastic property mismatch between differently angled plies. O'Brien [14] experimentally compared the difference between local delaminations occurring within the specimen bulk due to a matrix crack, and edge delaminations. The edge delaminations were found to propagate in a stable manner, whereas local delaminations from matrix cracks created local stress concentrations that led to a premature laminate failure strain below that of the primary load bearing plies. For tension–compression (T–C) fatigue, damage accumulation and thus material degradation is known to be more rapid than in T–T testing. [7] For multidirectional laminates, failure has been observed in both tension, by stress overload, and in compression, by buckling. In both cases the final failure was facilitated by existing extensive delaminations [15].

Voids are commonly present in composites either due to the manufacturing process, that leaves air trapped in the laminate during the curing cycle, or by nucleation from volatiles during processing [16]. Pre-impregnated (prepreg) composites are known to be particularly susceptible to air entrapment, particularly for the thick laminates used in wind turbine blades [17]. In order to assess the effect of voids on material performance, researchers have manufactured specimens with a range of different void contents. A common technique used to achieve this is to alter either the vacuum pressure on laminate during its cure cycle [18,19] or, if an autoclave is being used, alter the external pressure on the laminate [20,21]. By reducing the vacuum or autoclave pressure, a poorer laminate quality with a greater void content is produced. Although this technique ensures a spread in void fractions and thus an apparent assessment of their effect on performance, it is not clear whether the results are directly applicable to manufactured composites, as other factors are also influenced by changing the process conditions. In terms of resulting material properties, critical void levels below which mechanical performance is not affected have been suggested as between 1% and 4% in various studies [22–24]. Whether void content is more of a concern to static or fatigue properties is an area of disagreement, with some studies concluding that the static performance is largely unaffected by voids [25], while others report the same order in the reduction of both static and fatigue performance [18]. Studies explicitly relating to fatigue include that of Prakash [26] who performed axial fully reversed ($R = -1$) tests on unidirectional CFRP. It was hypothesised that voids, along with other damage, contributed indirectly to reduced fatigue performance through their poor heat dissipation properties. No quantitative analysis was performed. Chambers et al. [18] did perform quantitative analysis; controlling the void content through varying the cure cycle of the composite. Both static and flexural fatigue performance were found to deteriorate with increasing void content, however the authors argue that this global percentage view is too simplistic and that factors such as void size, shape, and distribution must be considered. Mandell and Tsai [27] also concluded that the overall void content view was inadequate, and that void size and shape must be considered. A critical void size was proposed, above which fracture mechanics based crack growth can be used to assess its influence, while below which the void simply contributes to a reduction in the cross-sectional area of the specimen. A number of studies have investigated the shape of voids, and possible correlation with material performance [18,21,27]. Aspect ratio has been the main shape parameter characterised, with 2D optical micrographs used to calculate this parameter. Studies have found aspect ratio increasing with void size, an unsurprising result considering the constrained nature of the voids between fibre tows. Chambers et al. [18] observe that void aspect ratio itself is not a good measure of void population, as the majority of voids have very low aspect ratios due to their small size, a result that is confirmed by Zhu et al. [21]. It is stated that the maximum aspect ratio is a better metric as it corresponds to the larger voids. Despite this, no work has identified a definite link between aspect ratio and performance. The difficulty associated with assessing a void's true 3-dimensional shape through optical microscopy could be responsible in part for this lack of understanding. Voids are generally agreed to be more detrimental to fatigue performance in compression than tension, where the damage mechanisms are usually fibre, rather than matrix dominated, at least in unidirectional materials. Overall there is a noticeable absence of literature on the effect of voids, especially when concerned with fatigue. Moreover, the studies that do investigate fatigue are usually limited to unidirectional carbon fibre composites, and the effect of voids in multidirectional laminates remains largely unknown.

3. Material and methods

Prepreg glass fibre–epoxy specimens (150 × 25 × 7 mm), representative of material used in wind turbine blade surfaces, with a gauge length of 28 mm and a layup of $[0/+45/-45]_{3s}$ were studied. In addition to these directional plies a "fleece" resin rich layer containing randomly orientated fibres, used to improve the surface finish of the composite, was present adjacent to each [0/+45/−45] ply group. The prepreg laminate was cured under vacuum but without the use of any external pressure. The cure cycle had two dwell temperatures, the first at 90 °C for 2 h, and a second at 120 °C for a further 2 h. Temperature ramp rates of 1.5 °C/min were used. 2 mm thick aluminium alloy was used for end tabs, adhesively bonded using Araldite™ 2011 and post-cured for 30 min at