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Effects of geometric non-linearity on energy release rates in a realistic wind turbine blade cross section

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ABSTRACT

Most wind turbine rotor blades comprise several adhesively connected sub-components typically made from glass fibre reinforced polymer composite materials. It is a well-known fact that wind turbine blades are prone to fail in their adhesive joints. However, owing to the complexity of their structural behaviour, little is known about the root causes of adhesive joint failure. This paper investigates the effects of geometrical non-linearity on energy release rates (ERRs) of transversely oriented cracks present in the adhesive joints of a wind turbine rotor blade. Utilising a computationally efficient numerical slice modelling approach, the Virtual Crack Closure Technique (VCCT) is used to compute Mode-I and Mode-II ERRs induced by bi-axial bending. Generic critical loading directions are identified; these may have far-reaching consequences for blade design, analysis and testing.

1. Introduction

From a structural mechanics perspective, wind turbine rotor blades are thin-walled, multi-cellular, glass fibre reinforced cantilever beams. The aerodynamic requirements of a wind turbine rotor blade dictates a complex surface geometry, including taper and twist. Glass fibre reinforced polymers usually serve as the main structural material because of their high specific strength, relatively low cost and shapeability. The anisotropy of these materials contributes to the complexity of the structural behaviour. Additionally, the loads experienced by the blades are governed by the complex dynamic, aero-elastic behavior of wind turbines. Finally, wind turbine blades deform extensively, with tip displacements reaching up to 20% of the blade length. As a consequence, geometrically non-linear effects must often be considered. All factors named above – complex geometry, anisotropic material behavior, complex loading and geometrical non-linearity – contribute to the complex structural response of wind turbine blades.

Wind turbine blades usually consist of several separately manufactured sub-components which are joined adhesively during assembly. Mere empiricism based on proprietary inspection reports and wind turbine blade damage documentations such as Ataya and Ahmed [1] show a high probability of adhesive joint failure – some earlier than expected. According to an NREL report [2], the contribution to the total downtime of wind turbines due to rotor issues ranges from 8% to 20%. The considerable costs arising from repair or replacement of blades emphasises a strong need for research on mitigation of adhesive joint failure in order to increase blade lifetime. Therefore, fracture analysis of adhesive joints in wind turbine rotor blades is an increasingly important aspect of the blade design process.

Although the research demanded by manufacturers and operators is high, literature, on the other hand is quite tacit about damage investigation of adhesive joints in blades in general, and practically non-existent for a realistic lifetime prediction. The reasons for this lack of knowledge are manifold and not solely attributed to the aforementioned structural complexity. An additional reason for this knowledge gap is due to manufacturing techniques and quality of production; these influence the likelihood of flaws, imperfections, tolerances, residual stresses that occur during curing and so forth. These factors, to name only a few, are known to have considerable impact on the fracture behaviour of adhesive joints but are hard to evaluate during the design process.

In principle, full 3D finite element models are able to capture the complex structural behavior of wind turbine blades to a large extent. However, these models reflect a dilemma caused by the limits set by computational efficiency in conjunction with the high mesh discretization levels (i.e. large number of degrees of freedom) demanded by fracture analysis. Although literature provides various advanced numerical fracture analysis tools for composite materials such as cohesive zone modelling, such models – when applied to full 3D blade models – are computationally extremely expensive. As a consequence such models are hardly used outside academia.

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To date, three different approaches are used to circumvent the computational limitations that appear in fracture analysis of large complex structures: The sub-modelling technique, the semi-analytical method and cross-sectional analysis.

In the sub-modelling approach, a small part of the structure (the sub-model) is modelled with high mesh resolution, while the global model uses a much coarser mesh. The solution of the global model is then interpolated onto the boundary of the sub-model. Fracture analysis is subsequently conducted on the sub-model as demonstrated and discussed by Haselbach [3] and Haselbach et al. [4].

In the semi-analytical approach, nodal forces in the vicinity of the adhesive connections are obtained from 3D models with a low degree of modelling detail and low mesh resolution. Subsequently, these forces are applied to analytical fracture models which resemble the actual joint geometry in the blade. A practical application of this method on adhesive joints in wind turbine blades was presented by Corre [5].

In the cross-sectional analysis approach only a thin cross sectional slice with a high level of detail and mesh resolution is modelled. The designation *thin* means that the thickness is small in comparison to the cross-section dimensions. The theoretical basis of the cross-section slice approach used to study ovalisation effects of thin-walled tubular cross sections originates with Kármán [6] and later Brazier [7]. Checchini and Weaver [8] were the first to numerically analyse a symmetric multi-cellular cross-section slice of a wind turbine blade. In the slice approach, displacement and force boundary constraints are applied to the cross-sectional faces such that the conditions of beam theory for the prevailing bending load case are satisfied.

Clearly, all three methods have drawbacks along with their advantages. The cross-section slice approach was found to be most suitable for investigation of geometric non-linearity affecting adhesive joints in a generic wind turbine cross section. Therefore, the pros and cons of its application will be briefly discussed. The striking advantage of the cross-section slice approach is a high mesh discretization level and level of detail without compromising computational efficiency. Changes of geometry are less cumbersome when compared to 3D models. Both geometric non-linearity and material non-linearity can be evaluated. Furthermore, this approach lends itself to the application of advanced fracture analyses tools for crack propagation analysis such as cohesive zone modelling and other methods as treated by Riccio [9].

The disadvantage of the cross-section slice approach is that local buckling effects (e.g. wave formation along the trailing edge) or effects arising from taper and twist of the blade are disregarded. Moreover, cracks are assumed to be transversely orientated where the crack front length must be assumed to be in the order of the blade length. Local effects of cracks with a short front length cannot be captured, as the stiffening effect from neighbouring un-cracked cross sections is disregarded.

The following influenced the investigations performed in this paper: It was known from both experimental blade research and from numerical analyses [10,11] that blades that naturally undergo large deformations experience geometrically non-linear in-plane warping deformations that might be responsible for adhesive joint failure. An analytical investigation of geometrically non-linear effects on a simple cross-section as discussed in [12] supports this suspicion. These investigations suggest that of all six cross-section forces, bi-axial bending (i.e. M_x and M_y) is the main contributor to Mode-I and Mode-II ERRs in trailing edge cracks – provided that local buckling is suspended. This paper consequently seeks to corroborate these analytical findings numerically on a realistic wind turbine blade cross section. The adopted slice approach served the aim of this paper to scrutinise the effects of geometric non-linearity on the energy release rates (ERRs) in transversely orientated pre-cracks present in all main adhesive joints of a generic wind turbine cross section. Note that it was not within the scope of this paper to conduct crack growth analyses but rather to use ERRs as indicator, giving insight into generic structural non-linear warping behaviour and its effect on adhesive joints.

For this purpose, a single section located at a radial position of 62.39 m of the DTU Wind Energy 10 MW light rotor reference wind turbine blade was chosen. A detailed description of the blade appears in Bak et al. [13]. The adhesive joints were modelled with a high degree of detail, typical of classic blade design approaches. Fracture analysis was conducted on the trailing edge joint, the leading edge joint as well as on the four cap joints. Due to similarities in behaviour the results of only four key-joints (see Fig. 1) are presented.

The *Virtual Crack Closure Technique* (VCCT) was used to compute bending-induced ERRs in cracks that were introduced in the adhesive of six joints. Based on the obtained results, critical loading directions and generic in-plane cross-section deformation behaviour is deduced and subsequently discussed. The paper concludes with a summary of findings which facilitate fracture analysis of adhesive joints in wind turbine blades, that might lead to improved blade designs.

2. Calculation

2.1. Slice model

The DTU Wind Energy 10 MW light rotor reference blade is 86.366 m long and made of glass fibre reinforced composites; balsa wood is used as the sandwich core. The properties of the composite materials (Uniax, Biax and Triax) listed in Table 1 are typical for the multi-directional plies.

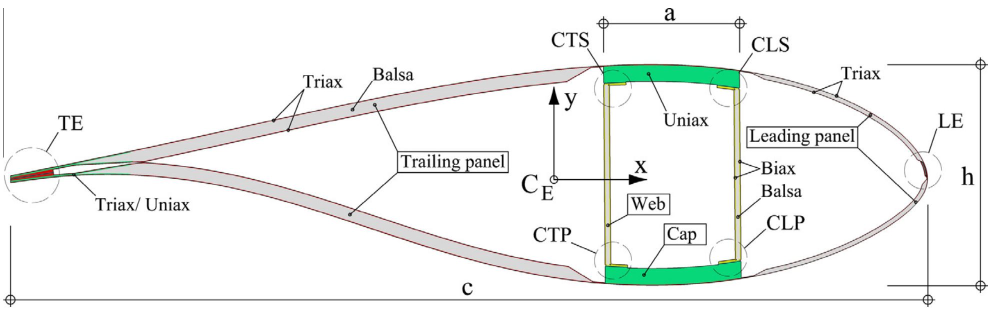

Fig. 1. Cross section at 62.39 m showing main structural parts and the associated material assignments and global coordinate system with origin at elastic centre. Six typical adhesive joints with location denoted as trailing-edge (TE), cap-trailing-suction (CTS), cap-leading-suction (CLS), leading-edge (LE), cap-leading-pressure (CLP) and cap-trailing-pressure (CTP) were modelled.