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The effect of delaminations on local buckling in wind turbine blades

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A R T I C L E I N F O

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A B S T R A C T

In this article the effect of delaminations on the load carrying capacity of a large wind turbine blade is studied numerically. For this purpose an 8.65 m long blade section with different initial delaminations in the main spar was subjected to a flapwise dominated bending moment. The model was setup in Abaqus and cohesive elements were chosen for modelling delamination growth.

For initial delaminations with a width of 30–50% of the cap width the study showed that delamination close to the surface started to grow in load ranges of normal operation conditions and led to local buckling modes. The local buckling caused high strains and stresses in the surrounding of the delamination, which exceeded the material design properties and therefore should be considered as dangerous.

Delaminations placed near the mid-surface of the cap did not have a significant effect on the blade response under normal operation conditions. In the simulations the static load exceeded the design load by more than 40% before delamination growth or cap buckling occurred.

It could be concluded that delamination induced near-surface buckling modes have to be considered critical due to an onset of local sublaminate buckling below the design load level.

1. Introduction

Areas of poor or no bonding in the interface between adjacent layers of a composite material are defined as delaminations. These interlaminar gaps/cracks normally originate from manufacturing flaws, areas with high stress concentrations around structural discontinuities such as holes, notches, ply drops or connections, or from impact damage during production, transport or service [1–3].

Delaminations embody a local separation of the laminated composite structures into sublaminates. The critical buckling load of the sublaminates may be well below the critical buckling load of the original structure. Consequently, the presence of delaminations may lead to a reduction of structural stiffness and strength. Due to this delaminations in laminated composite structures are considered to be the most critical type of damage that composite structures under compression can experience [4–6].

Delaminations in composite structures can trigger different buckling mode shapes, which poses different levels of danger to the structure. Considering buckling on a panel level the buckling behaviour of the structure with a delamination can be divided into local and global buckling modes (see Fig. 1) as well as into other combinational modes. A local buckling mode shape represents deformations of mainly one sublaminate on one side of the delamination. This local buckling mode will then introduce bending of the buckled sublaminate and reduce its load carrying capacity. Therefore, the other sublaminate will be subjected to higher compressive loading and additionally experience bending caused by the adjacent buckled sublaminate [7]. Higher ply stresses than in a sound structure will therefore occur, the consequence being that a reduced failure load of the composite structure under compression will arise. A significant reduction of the global critical buckling load can occur. The strength and stiffness reduction can be linked to the initial buckling of the structure. Local buckling typically occurs when the delamination is large and close to the surface (thin sublaminate on one side), which allows one part of the structure to buckle locally; whereas the remaining structure (basic laminate/thick sublaminate) does not buckle. For smaller delaminations located closer to the mid-surface global buckling predominantly occurs, wherein both sublaminates buckle towards the same side.

Under operation conditions wind turbine blades experience high aerodynamic loads, which lead to blade bending. The loading introduces compression on the suction side and tension on the pressure side of blades in normal operation. The loading-carrying

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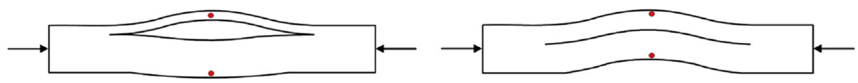

Fig. 1. Left: Local buckling mode (local cap opening); Right: Global buckling mode (full cap buckling); figure from Ref. [22]. The red dots symbolise displacement evaluation points. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

structure providing the blade with sufficient strength and stiffness often consists of a main spar and shear webs integrated into the aerodynamic shell. Usually the main spar is made of fibre composite materials, where most of the fibres are oriented in longitudinal direction. Often glass fibres or glass and carbon fibre combinations embedded in epoxy resin matrices are used, providing the composite structure with a high strength-to-weight ratio.

Delaminations may be found within the main spar of the blade. Overgaard et al. [8,9] e.g. investigated experimentally and numerically the structural collapse of a wind turbine blade and came to the conclusion that the structural collapse was caused by multiple local buckling-driven delamination processes. For an accurate assessment of detected delaminations based on size and location in wind turbine blades, guidelines and recommendations are needed.

In order to understand the effect of delamination under compression on laminated composite materials several tests and studies have been conducted. Short et al. [7] tested small glass-fibre-reinforced plastic test specimens, ran Finite Element simulations and developed simple closed-form models for isotropic materials. They also created for flat and curved test specimens a delamination induced buckling mode map for varying delamination sizes and through thickness positions differentiating between local and global.

Studies on the behaviour of delaminations in rectangular composite panels with an initial delamination under compressive loading were carried out by Branner and Berring [10]. They compared experimental findings with a numerical parameter study. Branner and Berring created a buckling mode map for panels under in-plane compression similar to the load carrying flange in the main spar of a typical wind turbine blade. The study showed how the buckling mode shape depends on the size and on the location of the delamination through thickness.

Gaotti et al. [11] studied numerically the panel behaviour under uni-axial loading. They compared advanced numerical prediction methods with the simple models, where delaminations were modelled as disconnected finite element regions.

In all these studies the authors concluded that the panels under uni-axial in-plane loading experience a significantly reduced compressive strength in case of simply supported boundary conditions. Short et al. [7] also concluded that delaminations near the convex side lead to more significant strength reductions than delaminations near the concave side of the panel. Much work was done to address delaminations on component and panel level. However, due to the assumed boundary conditions used in the studies the authors were limited in drawing solid conclusions whether or not their results can be transferred to full scale wind turbine blade structures. Does a delamination in a main spar of a blade cause a similar strength reduction or does the surrounded structure compensate the local stiffness and strength loss up to a certain size of the delamination? A design criterion for how large and deep delaminations can be accepted without increasing the risk of blade collapse taking the surrounding structure into account is missing.

Such a criterion could help blade manufactures and turbine operators to decide whether a detected delamination can be accepted, needs to be repaired, or whether the blade must be scrapped.

The aim of this numerical study was to investigate how much the strength of a wind turbine rotor blade is affected by delaminations. Two different approaches were used to study the effect of delaminations, where one of the numerical approaches allowed interlaminar crack growth in order to achieve higher accuracy.

2. Methods

2.1. Modelling method

The DTU 10 MW reference wind turbine blade was used as a basis for simulating the effect of delaminations. The blade, described in detail in Refs. [13], has a lenght of 86.4 m and a root diameter of 5.4 m. The load carrying structure of the blade is based on two caps and two shear webs. For the studies an 8.65 m long section of the blade was used to investigate delamination behaviour under static load. The section represented the rotor blade in a distance from 41.65 m to 50.3 m from the root at radial position from 44.45 m to 53.1 m (see Fig. 2).

The blade section was modelled with four node shell elements (Abaqus element type S4) in the commercial finite element software Abaqus/CAE 6.12-2. The outer surface of the blade was used as the reference surface containing the finite element nodes ("node offset option") (see Fig. 3). Apparent material properties were assumed to represent the multi-directional plies instead of a more

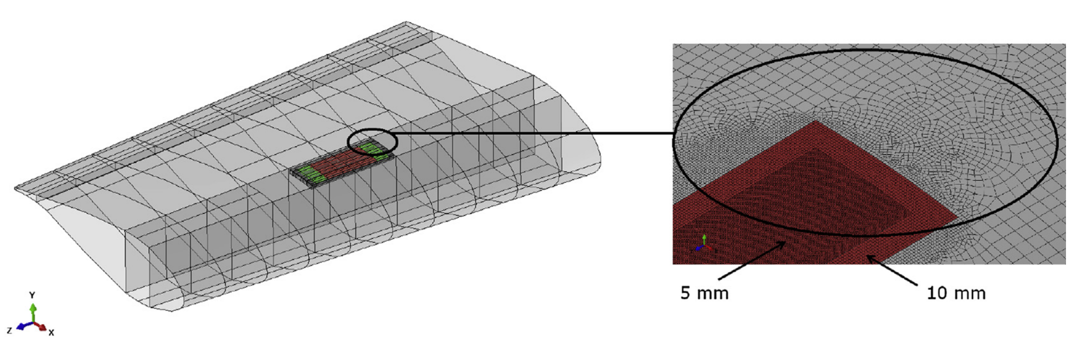

Fig. 2. Blade section shell model (grey) of the DTU 10MW Reference Wind Turbine including submodel (red). The submodel on the left picture is subdivided into two section cohesive zone I (red) and cohesive zone II (green). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)