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Damage tolerant design: failure and crack propagation in composites.

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1. Introduction

The most eye-catching trend for wind energy structural components is the up-scaling where new turbine designs have consistently provided larger towers, rotor diameters, and power ratings. The wind energy industry must compete with other energy sources by reducing the cost of energy, and the most cost effective way of increasing the power produced by a wind turbine is to increase the rotor diameter [1]. The industry relies on advances in materials technology and design philosophy to deliver the most cost-effective light-weight structures.

The historical design philosophy for reinforced polymer structures (main material of wind turbine blades) is based on conservative analysis methods, with large safety factors, underestimating the material properties, and considering only the linear behaviour of the material. As knowledge about the material and structure behaviour increased it became possible to safely adopt more advanced design philosophies, such damage tolerant design, where the material capability is fully exploited. This trend to more advanced structural design is described by *Braga*[2].

To achieve this, some research groups are working on a Multi-physics Global Model [3-7] as represented by the table 1. A Multi-physics Global Model is defined as a fluid-structural interaction model, which aims to integrate several phenomena models as aerodynamics, hydrodynamics, aero-elasticity, structural, vibration, energy output, control, etc. Moreover, damage tolerant design requires a good understanding of the material behaviour, and models capable to simulate the behaviour of the structure when damaged. However, this approach will not be achieved until all physical phenomenal present on the wind energy field are fully understood. Wind turbines are a multi-physics problem, and the complexity of the structure, the unpredictability of the wind and the lack of understanding of specific phenomena create challenges for the application of damage tolerance design method.

Table 1: Multi-physics Global Model scale main research topics.

Scale 100-1000 Km	Weather Forecast; Environment Conditions; Transport and Assembly; Maritime risk assessment; Maritime route planning;
Scale 1-10 Km	Aerodynamic design- Large Eddy Simulation; Turbulence; Wake effect between towers; Maritime risk assessment: ship collision;
Scale 10-500 m	Aerodynamic design- Blade profile shape; Floating structuring; Hydrodynamics; Aero-Hydro-elastic coupling: Interaction between wind, waves and the structural; Maintenance planning; Electric components; Gearbox; etc.
Scale 1-80 m	Structural design; Vibrations; Fatigue; Aero-Hydro-elastic coupling; Multibody analysis;
Scale 1mm-2m	Detail sub-structure design; Vibrations; Fatigues; Non-Linear Materials; Delamination; Bonded/connection joints; Manufacturing Plan;
Scale 1μm-10mm	Micro-mechanics; Material resistance; Sensor integration; Fibre-Matrix interface;

"Problem!! We don't fully understand the input, so how can we rely on the output?"
Is already accepted that a global model that compiles all the theory required and predicts when the damage will occur and how it will propagate is practically impossible to create. The solution starts by accepting the presence of damage and unpredictability, but still ensuring the structural health of each turbine.
"*Solution?? If we can't model the structure, we should monitor the material and understand damage propagation.*"
Detectable changes in response must exist between damaged and undamaged states, thus implying damage tolerance. Damage tolerance is a property emerging from the particular combination of structure design, loading environment, and material characteristics. Accepting that a distribution of damage types and locations can exist across a group of operating wind turbine blades, it follows that

each structure must be characterized individually with a unique "damage map" for that structure. Evaluating the severity of the particular combination of damage types requires models that describe the progression parameters for each type under the full range of operating conditions. Only in this way can condition based maintenance be effectively implemented.

2. Damage tolerant materials and structures

A damage tolerant behaviour is obtained when the stress-strain relationship is initial linear-elastic, but possesses significant non-linearity before failure. The structure will be designed to be loaded below the stress-value corresponding to the onset of non-linearity, however if the structure at some point is loaded beyond the linear-elastic regime, the resulting changes in stiffness will result in a measurable change in the local compliance of the structure. With respect to the propagation of a crack, damage tolerance implies that the crack growth should be stable, requiring that the applied load level for unstable crack growth should be significantly higher than the load level that initiates crack growth. A way to create damage tolerance is thus to make the crack propagation stable. For instance in the composite material/adhesive the delamination is accompanied by the formation of a crack bridging zone, where intact fibres connect the crack faces behind the tip, thus increasing the energy required for crack propagation (Damage tolerance mechanism) [8].
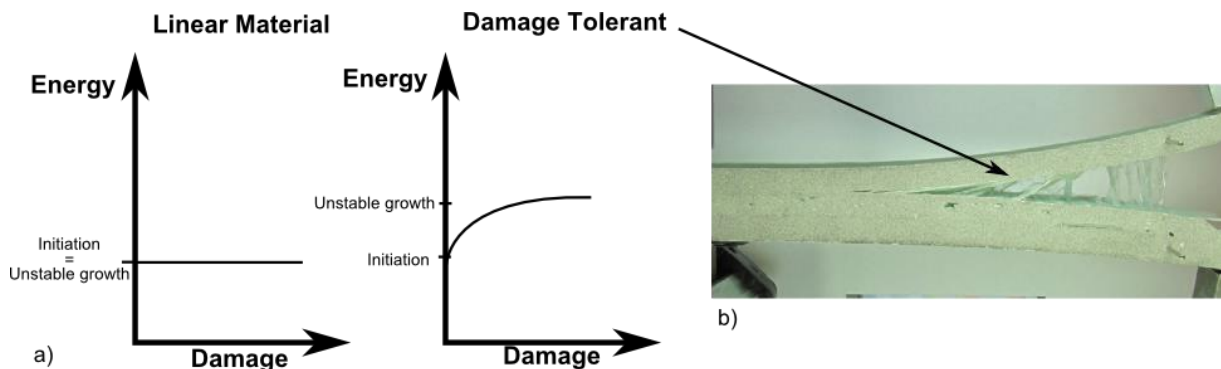

Figure 1: a) Conventional (Linear) material design philosophy vs Damage tolerant design; b) Damage tolerance mechanism- Fibre bridging.

With damage tolerant design philosophy the designers have the opportunity to create structures that can operate safely without propagating damage present in that structure, in this way they can fully exploit the material capability leading to structural optimisation.

3. Failure and crack propagation

In this study, the damage tolerance approach in wind turbine blade sub-structures was addressed, focusing on the crack growth mechanisms and detection methods. The trailing edge of the blade can develop damage in the composite material and adhesive interface. The delamination is accompanied by the formation of a crack bridging zone (Damage tolerance mechanism) [8]. A finite element model of the crack growth mechanisms in a double cantilever beam (DCB), representative of the trailing edge, was developed, where different fracture modes were addressed. Experimental tests were conducted in order to fully characterize this structure and support the model. Then a crack monitoring technique was implemented using Fibre Bragg Grating (FBG) sensors in order to track the crack and its propagation. This monitoring approach was incorporated into the finite element model (that was developed before) in order to predict the sensor output and extrapolate to a real trailing edge case. This sensor-structure makes possible to study the application of this monitoring technology in different components/ locations, with the objective of tracking different types of damage, as showed in figure 2.
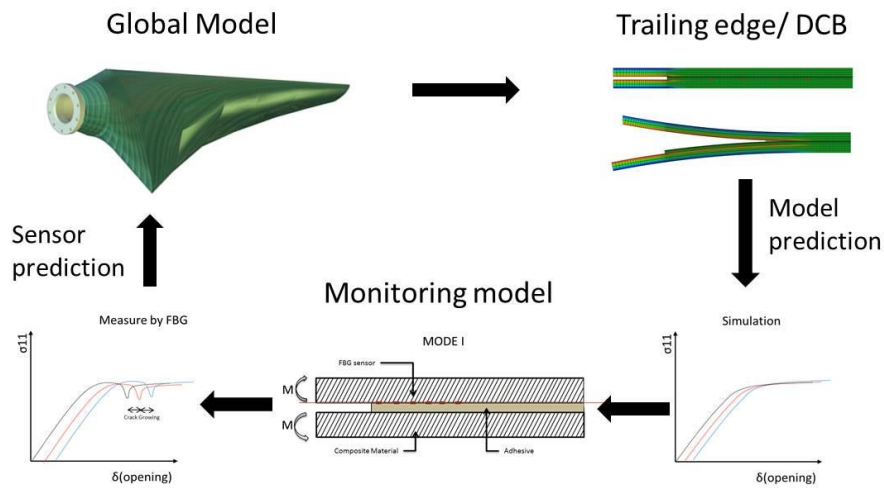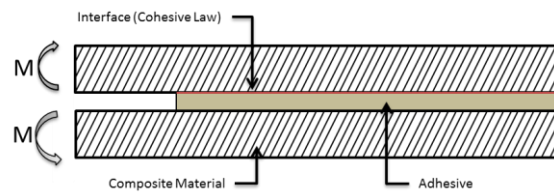
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Figure 2: Modeling scheme of crack growing mechanisms and detection methods.

a. Finite element model and Sensor technology:

A 2D and 3D double cantilever beam (DCB) finite element model was developed in order to represent the crack growth phenomenon, based on a real trailing edge configuration used by the *DTU 10MW Reference Wind Turbine* [9]. It was used cohesive elements that describe the cohesive law that governs the crack growth mechanism. In table 2 the materials properties used in the DCB model is shown.

Table 2: Scheme and materials properties used in the DCB model.

Composite Material		Interface (Cohesive Law)		Adhesive	
Triaxial Fabric (Composite)	Uniaxial Fabric (Composite)	Elastic	Damage (Quadratic stress)	Damage Evolution	Elastic
E_1=44.3 GPa; E_2=E_3=12,9 GPa; v_{12}= v_{13} =v_{23}=0.23; G_{12}=G_{13}=G_{23}=4393	E_1=23.8 GPa; E_2=E_3=15.05 GPa; v_{12}= v_{13} =v_{23}=0.513; G_{12}=G_{13}=G_{23}=4.393 GPa	K=4.2E12 Pa;	σ_n = 2.64 MPa ; σ_t= 22.15 MPa	δ_1 =1.4 ; $\delta2$ =0.37 ;	E=4.56 GPa; v=0.35

Where *E* is the Young's modulus, v is the Poisson's ration, *G* the shear modulus, *K* Penalty stiffness, δ displacement (opening) at failure, σ_n and σt the normal and shear traction.

b. Sensor technology:

Fibre optic sensors, such Fibre Bragg Gratings (FBG), can be embedded into the composite materials/adhesive, are virtually non-intrusive to the structure, and have the possibility to measure several points in a single fibre (multiplexing). This makes FBG's the perfect type of sensor to track the growing of certain damage types. A Fibre Bragg Grating (FBG) is formed when a permanent periodic modulation of the refractive index is induced along a section of an optical fibre, by exposing the optical fibre to an interference pattern of intense ultra-violet light[10]. The photosensitivity of the silica exposed to the ultra-violet light is increased, so when the optical fibre is illuminated by a broadband light source, the grating diffractive properties are such that only a very narrow wavelength band is reflected back.

When any external phenomenon creates a change on the grating, like temperature, strain, compression, non-uniform strain fields, etc. this will create a change in the reflected light. However, different phenomena acting on the grating will make different changes to the sensor response, like a fingerprint, so it will be possible to track specify phenomena, which are characteristic of damage.

c. Experimental validation:

After the FEM model been successful setup in order to represent the crack growth on the DCB specimen under the different loading conditions (Mode I/II). A dedicated algorithm predicted the sensor output, which allowed us to determine the presence of damage and it growth.
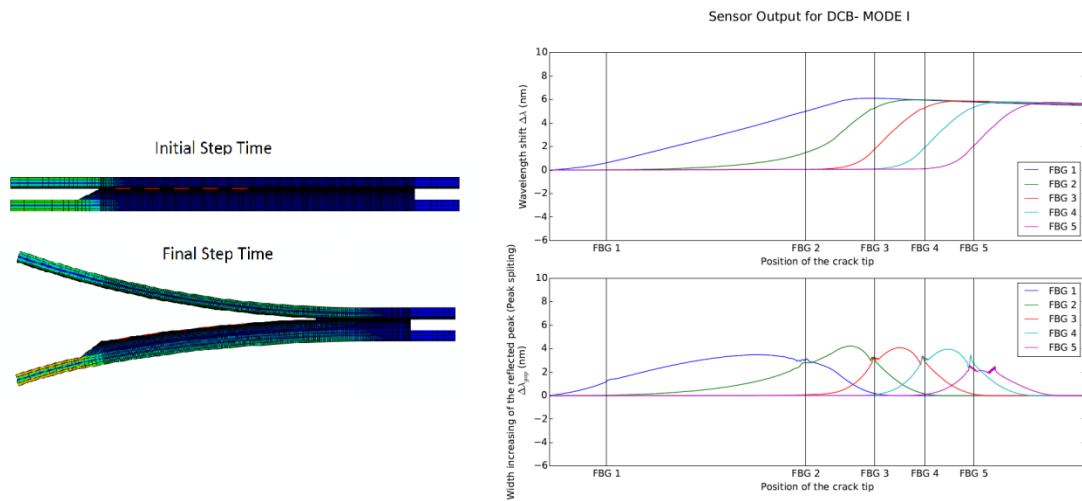

Figure 2: FEM model Sensor output for a Mode I loading case.

Then the same material/sensor configuration was tested in order to validate the pair structural-sensor model. The test was conducted using a double cantilever beam, as described by Sørensen [11] loaded in order to produce pure Mode I, Mode II and Mixed Mode fracture.

4. Results:

A good agreement between the FEM model and the experiments was found. The FEM model was able to represent the crack grow under the different loading cases. Also the sensor output model match the experiments, showing a specific sensor response ("fingerprint") when under the effect of a crack.
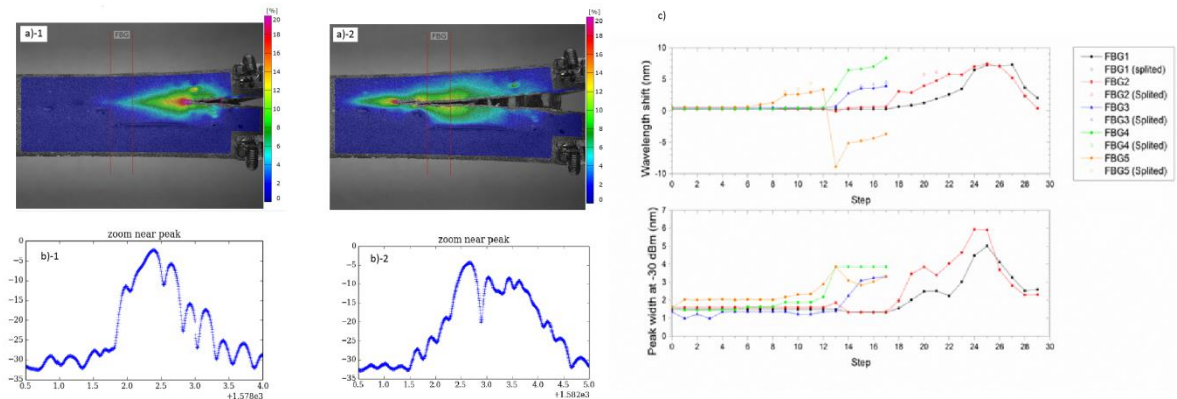

Figure 3: Experimental results for a Mode I loading case. a) Digital Image Correlation technic, b) FBG reflected peak, c) FBG sensor response.

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5. Conclusion

In this article we present an approach where the use of damage tolerant structural design and damage tolerant materials combined with an embedded FBG can detect damage evolution. This concept eventually lead to a condition monitoring maintenance, which consists of the detection of damages by sensors, characterization of damage (type and size), model predictions of residual life, giving information that enables decision-making with respect to whether a damage blade should be repaired or replaced.

The crack growth phenomenon on the trailing edge of the blade was successfully modelled, representing with good accuracy the fracture mechanisms present. A good agreement between the sensor output prediction through the FEM model and experiments was found. This demonstrated the presence of specific fracture features near the crack, which the algorithm and model was cable to predict and translate into a sensor response change.

These experiments validate the coupled *structure/sensor* model, so it becomes possible to study the application of this monitoring technique in other locations, predict the sensor output and track different damage features. The application of damage tolerant materials and structural monitoring can lead to safe operation of loaded components even when in damage condition.

6. Acknowledgment

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