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Published in: Proceedings of EWEA Offshore 2015 Conference

Publication date: 2015

Document Version Publisher's PDF, also known as Version of record

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Damage tolerant design and condition monitoring of composite material and bondlines in wind turbine blades: Failure and crack propagation.

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1. Summary
This research presents a novel method to assess a crack growing/damage event in composite material, in polymer, or in structural adhesive using Fibre Bragg Grating (FBG) sensors embedded in the host material, and its application in to a composite material structure: Wind Turbine Trailing Edge. A Structure-Material-Sensor Finite Element Method (FEM) model was developed to simulate the Fibre Bragg Grating sensor output response, when embedded in a host material (Composite material, polymer or adhesive), during a crack growing/damage event. This Structure-Material-Sensor model provides a tool to analyse the application of this monitoring technique in other locations/structures, by predicting the sensor output and deciding, based on this, the optimal sensor distribution/configuration.
2. Introduction
To compete with other energy sources Wind Energy need to reduce total cost per energy produced. The most cost effective way of increasing the power produced by a wind turbine is to increase the rotor diameter [1]. Thus, the Wind Energy industry relies on advances in materials technology and design philosophy to deliver larger but cost-effective light-weight wind turbine blades.

The conventional 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 some authors [2, 3].

This article proposes a methodology for a reliable design, damage detection and maintenance of wind turbine rotor blades using a condition monitoring approach and a damage tolerance design. This can be achieved by the use of a Damage Tolerant design, structural health monitoring and models describing crack propagation, which will enable the structure to operate despite the presence of damage and fully exploiting the capability of the material.

3. Fibre Reinforced Polymers
Fibre reinforced plastic (FRP) materials (composite materials) are the main material used in the production of Wind Turbine Blades. The main advantage of this material is the capability to be tailored for a specific application. This makes it possible to produce structures with enhanced properties and high level of customization, on characteristics such as lightweight, thermal expansion, chemical/corrosion resistance, fatigue behaviour, etc. This increased use of fibre reinforced plastic materials requires a proper understanding of the failure mechanisms. Delamination is one of the most important failure mechanisms and is considered the most widespread mode of life reduction.
**4. Damage Tolerant Design for Wind Turbine Blades**

Designing a wind turbine blade using a damage tolerance philosophy and a structural health monitoring system, will permit the structure to operate despite the presence of damage, such as due to fatigue, intrinsic/discrete damage, manufacturing defects, or severe accidental damage that occur during the operational life. This approach will enable a “real time” reactive maintenance of the structure. However, this will be achieved not by only accepting the presence of damage, but by controlling it and using the full mechanical capability of the material and structure.

A damage tolerant behaviour is obtained when the stress-strain relationship is initial linear-elastic, but possesses significant non-linearity before failure. This 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, as showed in figure 1.

![Figure 1: Fracture Energy Vs Crack Extension: Damage tolerant design.](image)

A way to create damage tolerance is thus by making any crack to propagate in a stable and controlled way. 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, as presented in figure 2 [4].
5. Delamination in Fibre Reinforced Plastic Materials

The use of damage tolerant design philosophy requires a proper understanding of the failure mechanisms in composite materials, being one of the most common type of damage the delamination/debonding (in composite material/adhesive interface). This delamination is accompanied by the formation of a crack bridging zone, as discussed before. It is possible to change the cohesive laws by changing the properties of microscale parameters. Observations suggest that fracture mechanics properties of fibre/matrix interfaces, as well as the fracture mechanical properties of interfaces between layers in laminates, play a central role in the fracture resistance. Mastering these properties is the key to optimising the fracture resistance of a wind turbine blade.

6. Wind Turbine Blade Structural Health Monitoring Concept Development

The aim of the present project is to develop a damage tolerance approach for wind turbine blade sub-structures, focusing on the crack growth mechanisms and detection methods. To do this, a finite element model of the crack growth mechanisms in a double cantilever beam (DCB), representative of a delamination on real blade trailing edge under different fracture modes was developed.

Afterwards, a crack monitoring technique was implemented using embedded Fiber Bragg Grating (FBG) sensors into the composite material/adhesive bonding, to detect cracks and its growth. Different features present in the crack mechanism that can induce a change in the FBG response were identified, making it possible to identify specific phenomenon that will only happen with the proximity of a crack, such as compression fields ahead the crack or non-uniform strain, and then identify the presence of such damage in the real structure.

Figure 2: Fibre bridging phenomenon.
## 7. Crack/Delamination Detection by Embedded Fibre Bragg Gratings

Fibre Bragg Gratings (FBG) is a very promising technology to track the presence of delamination/cracks in an operational FRP structure, due to its capability to be embedded in the material, without compromising the structural resistance. The FBG small size, 125 μm of diameter, makes it virtually non-intrusive to the material.

A Fibre Bragg Grating 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. 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 [5].

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 specific phenomena, which are characteristic of damage.

![Fibre Bragg Grating work principle](image)

Figure 3: Fibre Bragg Grating work principle.
8. Experimental Validation

Double Cantilever Beam specimens with the same material-sensor configuration as the model, were tested using a fracture testing procedure. The were instrumented with an array of FBG sensors embedded in the host material, and a digital image correlation technique was used to determine the presence of specific phenomena caused by the crack, and then correlate it with the FBG sensor, as showed in figure 4.

9. Finite Element Method Model

A Finite Element Method Model was developed to simulate the sensor output response of a Fibre Bragg Grating, when embedded in a host material during a crack growing/damage event. This sensor-damage-structure model provided a tool to study the application of this monitoring technique in other locations, by predicting the sensor output and deciding, based on this, the most optimized sensor-structure configuration.

It was modeled a Double Cantilever Beam (DCB) under different fracture modes, and the sensor simulated by an array of embedded FBG sensors, as showed in figure 5. This sub-model (DCB-trailing edge) can be extrapolated to a model of a full structure (Full Wind Turbine Blade), and simulates the response of sensors under different types of failure, as showed in figure 6.

Figure 4: FBG sensor response during crack growth.
Figure 5: Sensor Output FEM model.

Figure 6: Model scheme of crack/delamination detection by embedded fibre Bragg gratings.
10. Conclusions
In this article we present a new approach, where the use of damage tolerant structural design and damage tolerant materials combined with an embedded FBG can detect damage evolution.

It is possible to extract information from the sensor that is independent of the loading type, geometry and boundary conditions, which depend only on the proximity of a crack. This fact, allows the application of this monitoring system in general composite material structures. The prediction of the sensor response by the FEM model makes it possible to study the application of this monitoring technique in other locations, predict the sensor output, and decide on the optimized sensor-structure configuration.

This “Structure-FBG Finite Element Model” concept can have an impact in condition monitoring methodology and maintenance, by optimising the measurement by sensors, enabling more diverse and accurate damage detection, giving better characterization of the damage (type and size), and giving information for prediction of the residual structural life, and if possible, repair.

11. References


