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STRUCTURAL HEALTH MONITORING METHOD FOR WIND TURBINE TRAILING EDGE: CRACK GROWTH DETECTION USING FIBRE BRAGG GRATING SENSOR EMBEDDED IN COMPOSITE MATERIALS

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ABSTRACT

In this article a novel method to assess a crack growing/damage event in composite material using Fibre Bragg Grating (FBG) sensors embedded in a host material and its application into a composite material structure, Wind Turbine Trailing Edge, is presented.

A Structure-Material-FBG model was developed, which simulates the FBG sensor output response, when embedded in a host material, during a crack growing/damage event. This Structure-Material-FBG 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.

All the different features in the fracture (cracking) mechanism that can induce a change in the FBG response were identified. With this, it was possible to identify specific phenomenon that will only happen in the proximity of a crack, such as compression fields ahead the crack or non-uniform strain fields, and then identify the presence of such damage in the structure. Experimental tests were conducted to fully characterize this concept and support the model. Double Cantilever Beams (DCB), made with two glass fibre beams glued with structural adhesive, were instrumented with one array of FBG sensors embedded into the host material, and digital image correlation technique was used to determine the presence of the specific phenomena caused by the crack, and to correlate with the FBG sensor.

1 INTRODUCTION

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

The conventional design philosophy of 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 [1]. 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. The solution starts by accepting the damage and its unpredictability, however this requires monitoring technology to track the damage, by use of integrated sensors that will give information about the presence of damage in an accurate way, it's location and the type of damage.

This research presents a novel method to asses 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 DELAMINATION IN FIBRE REINFORCED PLASTIC MATERIALS

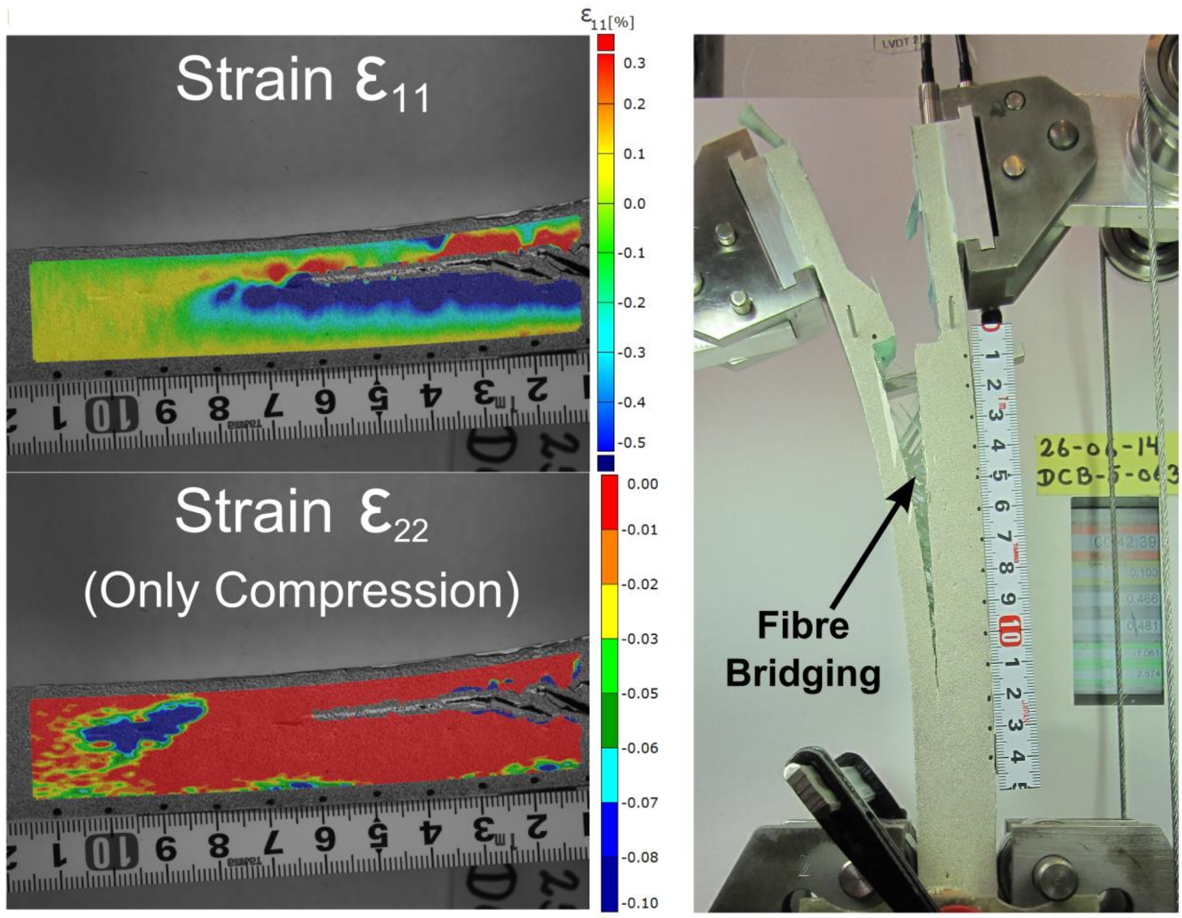

Figure 1: DIC measurement: strain distribution around a crack tip during delamination.

Interface fracture by crack growth along interfaces in laminate structures is called delamination and often is accompanied by the formation of a crack bridging zone. In the crack bridging zone intact fibers connect the crack faces behind the crack tip, increasing in this way the crack growth resistance, i.e. the energy required for a crack to grow is higher than that required to initiate it.

To be able to detect delamination/crack in FRP materials the sensor/monitoring system selected should be able to track specimen fracture features, which only happen in the vicinities of the crack independent of geometry or loading conditions. Thus, in order to link these fracture features with the measured parameters, the strain distribution around a crack tip during delamination was analysed using Digital Image Correlation (DIC), as shown in figure 1. DIC technique is a non-contact optical method that, by tracking changes in a random pattern on the specimen, can correlate it with deformation/strain of the material.

To study the delamination in FRP material, Double Cantilever Beam (DCB) specimens were tested in a fracture testing machine, developed by Sørensen [2]. The DCB specimens were loaded with different combination of Moments, which will give different type of fracture modes, simulating different crack/delamination cases. The DCB specimens were manufactured using two FRP material arms, made of unidirectional and triaxial glass fibre layers (SAERTEX UD and TRIAX), with a layup stacking of : [90/+45/-45/0_4/0_4/+45/-45/90], glued by a commercial epoxy structural adhesive (Epikote MGS BPR 135G/Epikote MGS BPH137G). A thin slip foil was placed in the edge of the structural adhesive, to act as a pre-crack and ease crack initiation.

3 CRACK/DELAMINATION DETECTION BY EMBEDDED FIBRE BRAGG GRATINGS

Fibre Bragg Grating (FBG) sensors are a very a promising technology to detect 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. FBG sensors, also have other interesting features, such high resolution, multiplexing capability, immunity to electromagnetic fields, chemical inertness and long term stability (fatigue behaviour).

As mentioned, during a crack/delamination event different fracture features will be present near the crack tip. Being able to identify and measure these specific phenomena with a FBG sensor is the key factor to correctly determine the presence of damage and it growth. Some authors [3,4], already described the different sensor output signals measured during all the different stages of crack growth, and identified the uniform strain, ε_{zz}, the compression strain, $\sigma_{x,y}$, and the non-uniform strain, $\varepsilon_{zz}(z)$, as the most important measurements that will allow crack detection and monitoring.

In figure 2, the three different stages of the FBG responses under a crack growth event are presented. First, before the crack reaches the proximity of the grating, figure 2a), the material will build-up strain, that will create a uniform wavelength shift in the FBG reflected peak. Next, a compression field is formed ahead of the crack tip due to the formation of a crack bridging zone, figure 2b). When this compression field reaches the grating area it creates a peak splitting of the FGB response. Then, when the grating is near the influence of the crack singularity, figure 2c), a non-uniform strain field will also modify the shape of the reflected peak. After the crack passes the FBG sensor, the shape of the reflected peak will go back to the original shape, and the sensor response will again be a simple wavelength shift, because at this stage only uniform strains will be present at the FBG.

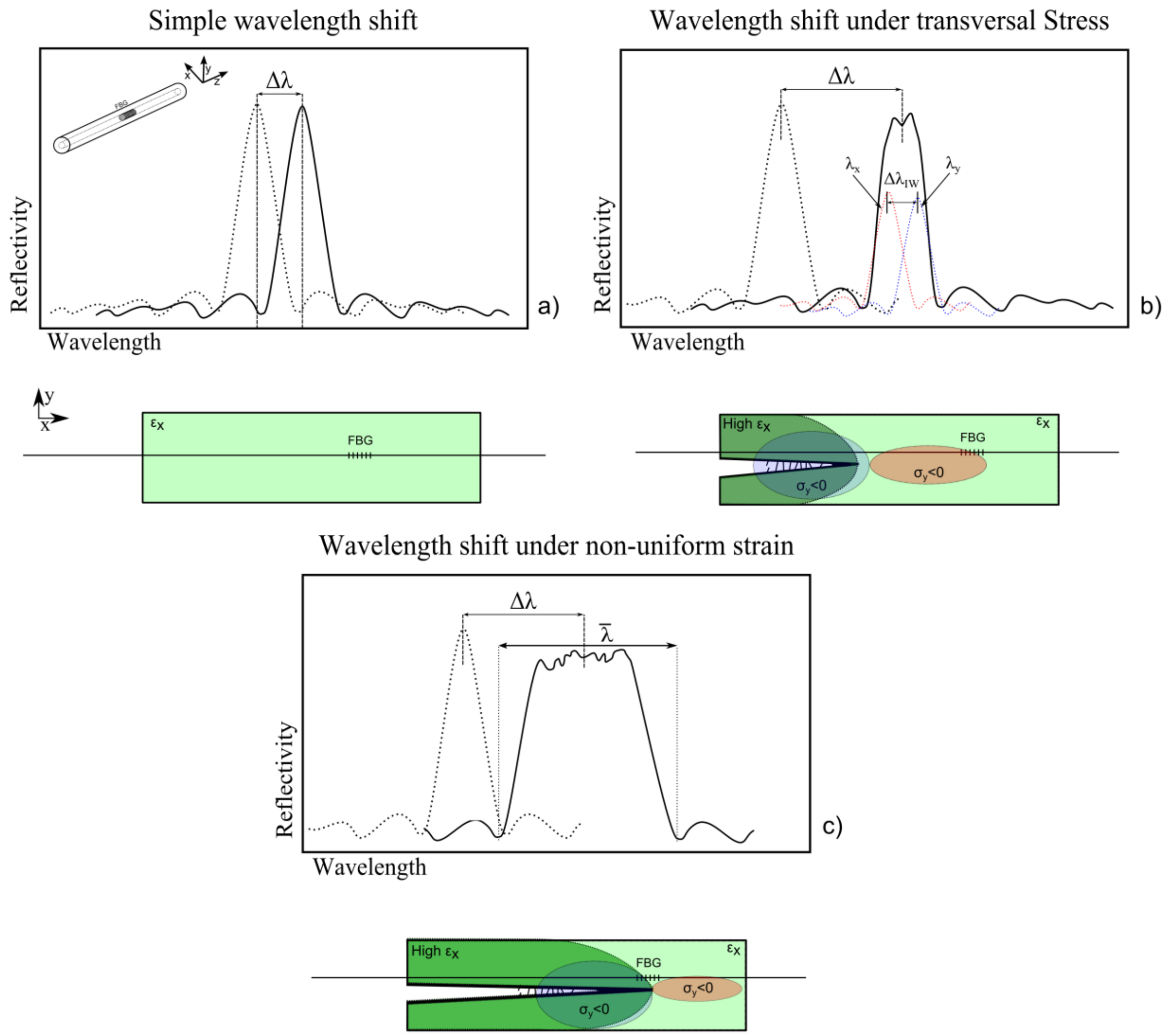

Figure 2: Different stages of the FBG response under a crack event.

4 FIBRE BRAGG GRATING WORKING PRINCIPLE

A Fibre Bragg Grating (FBG) is formed by a permanent periodic modulation of the refractive index 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 a very narrow wavelength band is reflected back.

The spectral response of a homogeneous FBG is a single peak centred at the wavelength λ_b. The λ_b wavelength is described by the Bragg condition [5],

$$\lambda_B = 2n_{eff,0}\Lambda_{,0} \tag{1}$$

where n_0 is the mean effective where refractive index at the location of the grating, the index 0 denotes unstrained conditions (initial state). The n_{eff} is the effective refractive index and Λ is the constant nominal period of the refractive index modulation.

3.1 FBG response: Uniform Strain

The wavelength shift $\Delta\lambda_b$ of an embedded FBG under a uniform variation of strain, ε_{zz}, along the fibre direction, and considering no temperature variation (during crack growth temperature variation is neglected), is given by the equation 2,

$$\frac{\Delta\lambda_b}{\lambda_b} = (1 - pe)\,\varepsilon_{zz} \tag{2}$$

where *pe* is the photoelastic coefficient of the optical fibre.

3.2 FBG response: Transverse Stress

As discussed, the compression field formed ahead of the crack tip will reach the grating area, which will create a peak split of the FBG reflected signal. This peak split phenomenon is due to a birefringent effect, which can be defined as the change of the refractive index n_{eff} in the two directions n_{effy} and n_{effx}, when the grating is subjected to a transverse force. The increase in the width of the reflected peak is given by the equation 3,

$$\Delta\lambda_{WV} = 2\Lambda\left|\Delta n_{effz} - \Delta n_{effy}\right| = \frac{\Lambda n_0^3}{E_f}\left[(1+\upsilon_f)p_{12} - (1+\upsilon_f)p_{11}\right]\left|\sigma_x - \sigma_y\right| \tag{3}$$

where $\sigma_{x,y}$ is the transverse stress, E_f is the elastic modulus of the optical fibre, v_f is the Poisson's ration, n_0 is the initial refractive index, p_{11} and p_{12} are the photo-elastic coefficients of the optical fibre.

3.3 FBG response: Non-Uniform Strain

A non-uniform strain changes the periodicity of the grating pattern along the sensor length, modifying the grating pattern configuration from "uniform" to "chirped". As demonstrated by Peters [7], in a uniform grating the applied strain will induce a change in both grating period and the mean index. These two effects can be superimposed by applying an effective strain of *"(1-pe)ε_{zz}(z)"*, similar to the first part of equation 2, but taking into account the strain variation along the z direction. Then it is possible to rewrite the grating period as:

$$\Lambda(z) = \Lambda_0\left[1 + (1 - pe)\varepsilon_{zz}(z)\right] \tag{4}$$

where Λ_0 is the grating period with zero strain. The non-uniform strain effect can be approximated by using the maximum and minimum strain values along the grating. So, the maximum grating period Λ_{max} and minimum Λ_{min} can be calculated using the equation 1. Thus, an approximated increase of the width of the reflected peak due to a non-uniform strain is given by combining equations 4 and equation 1:

$$\bar{\lambda} = 2n_{eff}\Lambda_{\max} - 2n_{eff}\Lambda_{\min} \tag{5}$$

5 APPLICATION OF THE FBG CRACK DETECTION METHOD

The aim of the present project is to develop a damage tolerance approach for wind turbine blade trailing edge, focusing on the crack growth mechanisms and detection methods. To achieve this, a numerical model that can predict the FBG output in a general crack growth situation was developed. This sensor-structure model makes possible to study the application of this monitoring technology in different components/ locations, with the objective of tracking different types of damage, as shown in figure 3. This model was incorporated into the finite element method model of a DCB specimen, based in a real trailing edge configuration used by *the DTU 10 MW Reference Wind Turbine,* which was experimentally validated.

The trailing edge was modelled as a 2D and a 3D Double Cantilever Beam, where different loading conditions (ranging pure Mode I to pure Mode II fracture modes) simulate the different fracture cases that can occur in this structure. The crack growth in the DCB specimens was modelled using cohesive elements, which describe the cohesive law that governs the crack growth mechanism.

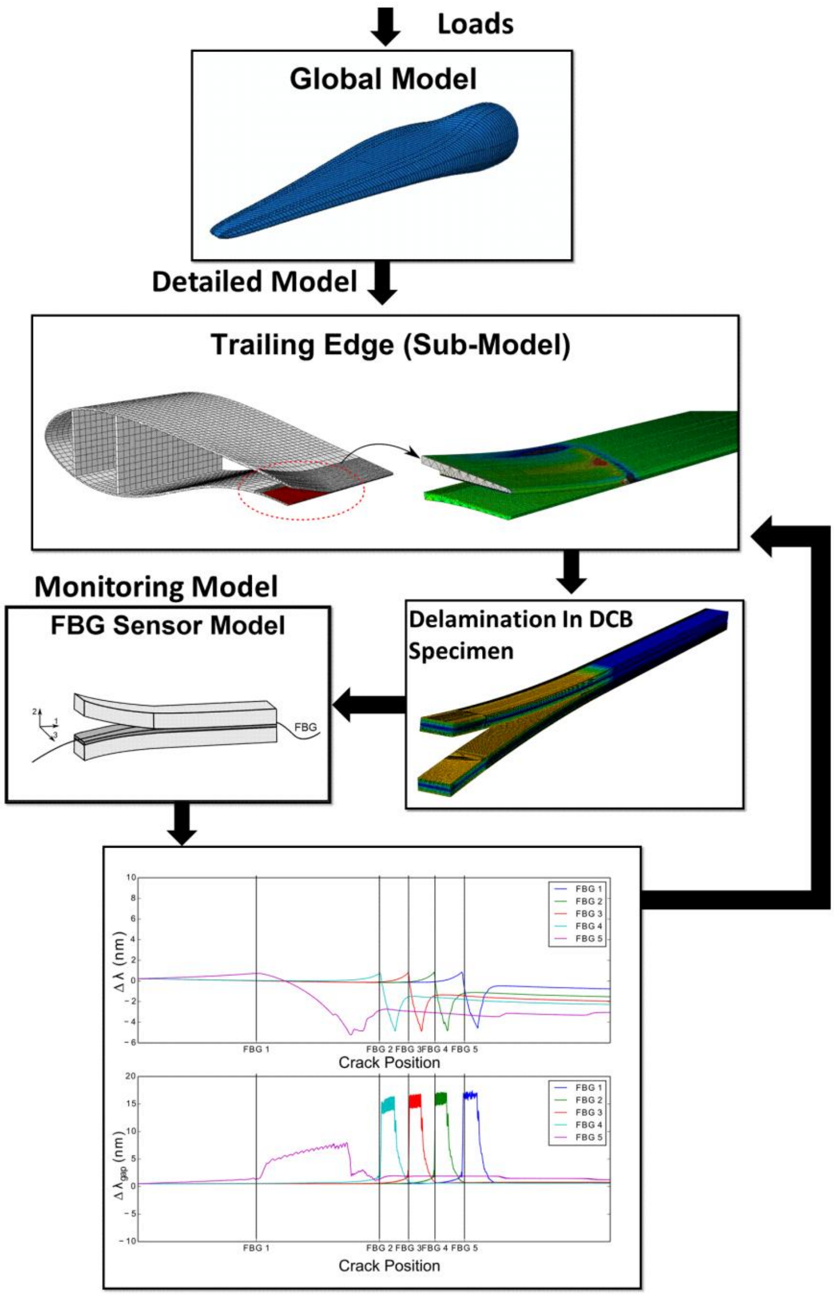

Figure 3: Model scheme of crack detection by embedded FBG sensors.

5.1 Model Validation

DCB specimens with the same material-sensor configuration as the model, were tested. The DCB specimens were instrumented with an array of FBG sensors embedded in the host material. A good agreement between the finite element model and the experiments was found. The FEM was able to represent the crack growth under different loading cases, and the sensor output model matched the experiments, as shown in figure 4, showing the expected sensor response to fracture phenomena, already measured by DIC technique.

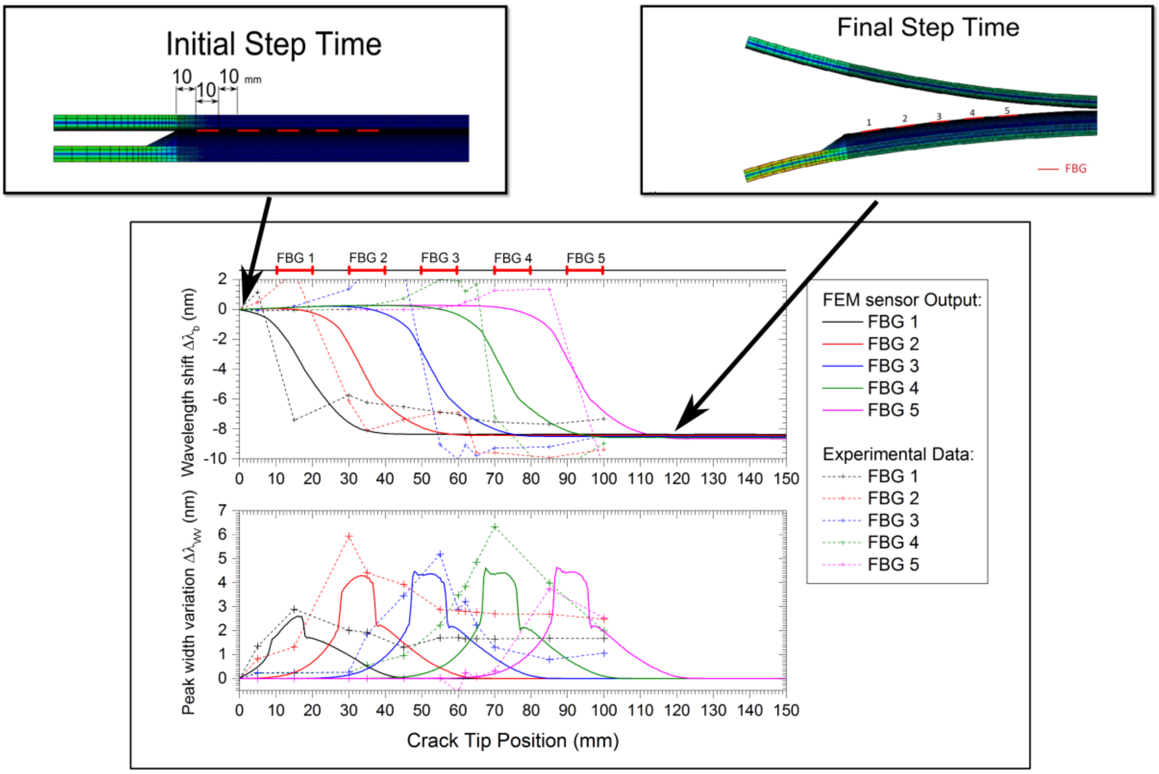

Figure 3: Model experimental validation: FBG Output prediction.

6 CONCLUSIONS

A new structural health monitoring approach where fibre Bragg grating sensors embedded in the composite material can detect and track cracks/delamination was presented.

Using the digital image correlation technique results, it was 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. The different FBG working principal were described, and identified that the uniform strain, ε_{zz}, the compression strain, $\sigma_{x,y}$, and the non-uniform strain, $\varepsilon_{zz}(z)$, are important measurements that will allow crack detection and monitoring.

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. So, it becomes possible to use damage tolerant structural design and damage tolerant materials combined with an embedded FBG sensors. Thus, integration of sensors and actuators into a structure becomes possible, leading to a smart structure capable to analyse and adapt to environmental conditions and adjust it operation requirements bases on the structural health data.

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.

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