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Measuring changing strain fields in composites with Distributed Fiber-Optic Sensing using the optical backscatter reflectometer

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ABSTRACT

Background/purpose: Measurements of strains in critical components are often required in addition to finite element calculations when evaluating a structure.
Methods: This paper describes how standard optical fibers, bonded to the surface or embedded in a laminate, can measure strain fields along the entire length of the fiber, using the optical backscatter reflectometer.
Results: A strain field measurement can be much better compared to simulations than the more common single point measurements with strain gauges or Bragg Gratings. Changes of the strain field can be related to damage development and can be used for structural health monitoring. Practical aspects of using the fibers are also discussed.
Conclusion: Distributed Fiber-Optic Sensing was successfully embedded and bonded to a composite joint. Adhesive damage was identified and the strain field agreed well with FE-Analysis.

1. Introduction

Knowing stresses and strains in a component is a fundamental aspect in every structural analysis. Numerical simulations, such as finite element (FE) analysis, are the most widely used methods for obtaining stress and strain fields, less frequently analytical methods are applied. Simulating stresses and strains of constructions can have many uncertainties, due to high stress concentration points, complicated geometries, interfaces and uncertainties in material properties. To verify models and simulations it is often desirable to obtain strains also from measurements directly taken from the component.

Understanding strain fields becomes even more important if damage or large local deformations develop during service life, since damage can change strain fields. On the other hand, if the change of the strain field due to damage is well understood, measuring the change of the strain field can be used as a Non Destructive Evaluation (NDE) method for characterizing the damage that has developed.

Measuring strain is well established, but still has its challenges. The most widely used method to measure strains is to apply electrical strain gauges (SG). Measuring strain gradients and strain fields is complicated and typically requires an array of small SG's at the region of the strain concentration (gradient) [1]. A SG measures an average strain over the gauge area. If the strain concentration is steep the gauge area may be too large to describe the slope properly. The main disadvantage of using arrays of SG's is, that the location of the strain concentration and principal strain direction need to be known in advance, because strain gauges need to be placed at the position of the strain concentration. If the strain concentration moves outside this array of SG, due to damage development, the strain concentration cannot be measured anymore. Further, a change in the load condition may change the direction of principal strain also causing a strain measurement to be misinterpreted.

Applying optical Fiber Bragg Gratings (FBG) is also a well established method for measuring strains [2]. The strain is measured over the length of the Bragg Grating. This fixed gauge length and position gives similar limitations as for electrical strain gauges (SG), when measuring steep strain concentrations. Since no electricity is used in the sensing area, FBG can be used in water, near magnetic fields and fire hazard areas. FBG can also be fairly easily embedded into polymers, adhesives and composite laminates [2].

A method well suited for measuring strain fields on a component's surface is Digital Imaging Correlations (DIC) [3], DIC uses stereo cameras that need to be placed at a stable position relative to the component. If sufficient accuracy is to be obtained, DIC tends to be limited to the laboratory. DIC is generally not suitable for

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permanent monitoring and it is not easily applied in the field. DIC can be used to verify the strain field deduced from numerical analyzes, and to monitor how the strain field is changing on the surface during loading or due to damage development. It is easy to detect crack initiation and propagation.

Photoelasticity is also used for measuring strain fields using transparent polymers and polarized light, but the method is more complicated than DIC and has fallen out of favor.

The optical backscatter reflectometer (OBR) is a fairly new equipment for measuring strains with optical fibers [4]. This equipment with its software allows continuous strain measurements along the entire length of the optical fiber and can be categorized as a Distributed Fiber-Optic Sensing (DFOS). It is a promising technology that can combine the simplicity of SG or FBG measurements with the advantages of DIC. This paper investigates first the accuracy of the method and shows subsequently two examples of how the OBR can be used to measure strain fields in composite-metal joints, to detect damage development and to investigate three dimensional strain fields. The accuracy study was done on a fiber-reinforced composite laminate with a circular hole in its center. A damage propagation study was performed on a fiber-reinforced laminate to metal single lap shear joint, and a three dimensional strain fields study was performed on a notched metal I-beam repaired with a composite laminate patch.

So far, the OBR has mainly been used on larger structures, including structures made of composites. A 40 m wind turbine blade was tested, and one optical fiber replaced 25 electrical strain gauges [5]. Six optical fibers were applied in parallel covering the whole wind turbine blade. The fibers were connected to the OBR interrogator with an optical multiplexer. Also one large 6.5 m beam was investigated, where the optical fibers were integrated into the compression flange surface and tested in four point bending. The data of 300 measurement points showed the well-known trapezoidal strain shape [6] for a four point bending test. Also delamination in smaller specimens were detected with good accuracy by the optical fibers [5]. The OBR was also used on a ship, an experimental catamaran, lying in a harbor [7].

2. Distributed Fiber-Optic Sensing (DFOS)

2.1. General

Fiber-Optic Sensing (FOS) is a broad field of sensor technologies developed through several decades. Common to all of them is that they interpret and analyze reflections of light emitted into optical fibers. Distributed Fiber-Optic Sensing (DFOS) measures a strain field using an array of sensors. Such an array can be built using standard FBGs, which can be integrated in a single optical fiber, typically up to ten gauges. Other techniques are using the Brillouin and Raman backscattered radiation, but the spatial resolution obtained is typically in the order of more than a meter [5].

This study used the Rayleigh backscatter pattern allowing a spatial resolution down to about a millimeter along the entire length of the optical fiber. The interrogator used was the optical backscatter reflectometer; OBR 4600 from Luna Technologies [4].

2.2. Optical backscatter reflectometer (OBR)

DFOS with OBR work with any regular telecom optical single mode (SM) fiber [4]. The optical fibers can be bonded to the surface or can be integrated/embedded into FRP composite laminates or adhesives.

In a simplified way, the OBR is sending laser light through an optical fiber. The light is reflected by the natural variations along the length of the fiber and acts as a unique fingerprint. The pattern of the reflections and the time of flight of the light is measured and stored in a computer and may be used as continuously distributed sensing points. If the fiber is exposed to mechanical strain the position of the reflection/sensing points will change, creating a slightly different reflection pattern. The new reflection pattern is also stored and compared/cross correlated with the original reflection pattern. This cross-correlation allows calculation of strains along the entire length of the fiber.

More accurately, the Rayleigh backscatter profile of an optical fiber is a result of a heterogeneous reflective index, randomly distributed along the length of the fiber. This is a result of the manufacturing of the optical fiber which gives a unique reflective profile over the whole length and is the optical fiber's fingerprint. This fingerprint gives thousands of potential sensing points distributed along the fiber and is unaltered until any external stimulus (like strain) causes a spectral shift locally in the backscattered pattern [8]. These shifts are used to calculate the changes in strain along the length of the fiber when compared to the unstrained reference state.

The OBR interrogator stores logged data (image) from the reflected light of the unstrained and strained fiber. The change of reflected light due to applied strain is analyzed by the system's software during post processing. The software defines many sensors along the length (sensing length) of the optical fiber. All the virtual sensors have the same gauge length and spacing between them. This is shown schematically in Fig. 1. Sensor spacing and gauge length can be virtually changed by the user in the post-processing software.

Strain is calculated as an average of the movements of the reflective pattern along the gauge length for each virtual sensor. Sensing length divided by the sensor spacing (set virtually by the user in the post-processing software) determines how many measurement points will be calculated. It describes how close the array of measurement points is placed. Since this is a continuous optical fiber the gauge area of two adjacent measurement points will overlap when the gauge length is larger than sensor spacing. When measuring high strain gradients a balance needs to be found between short gauge lengths for measuring the gradient and long gauge lengths for reducing the scatter in the results.

Which combination of gauge length and sensor spacing gives the best results, needs to be found for each measurement. This study used 5 mm gauge length and 1 mm sensor spacing. When very long gauge lengths and sensor spacing are chosen, strains along the optical fiber appear very smooth, but strain concentrations are smoothed out too much and may not be detected. If gauge length and sensor spacing are chosen too low, the data show much noise with peaks in tension and compression. The noise and scatter

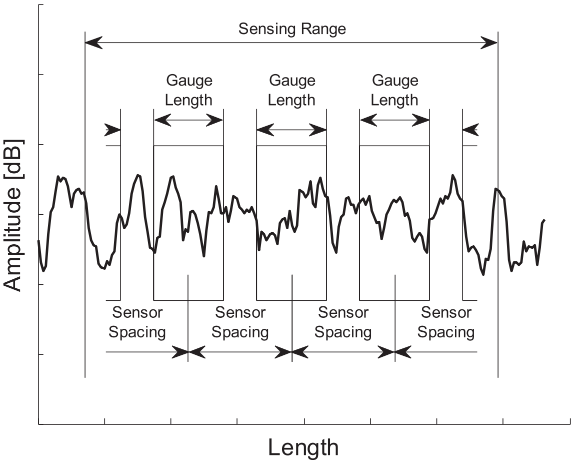

Fig. 1. Illustration of sensing range, gauge length and sensor spacing for OBR sensing.