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DAMAGE DETECTION IN COMPOSITE STRUCTURES FROM FIBRE OPTIC DISTRIBUTED STRAIN MEASUREMENTS

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ABSTRACT

Two approaches may be followed to obtain damage information from strain measurements:

1) To use multiple sensing points, and to reduce the huge amount of information by pattern recognition techniques, as PCA. (companion paper)

2) To use distributed sensing (OFDR of backscattered radiation), placing the plain optical fibre at the region where damage is expected. Because of its simplicity, this approach is very robust, and even its local nature, similar to the VCM, it may be of interest in some applications, like stringer debonding, or for identifying local damage by impacts around man-holes. One advantage of this approach compared to the former one, is that the structure does not need to be under load, it measures the residual strains caused by the damage.

Several experiments, done on real aeronautic composite parts, are presented, quantifying the POD, robustness and applicability of the technique.

KEYWORDS : *Rayleigh scattering, fibre optic sensors.*

INTRODUCTION

FBG (Fibre Bragg Grating) sensors, have been used for the last 20 years, and they have built up a confidence in its performances. FBGs can measure the strain with a similar accuracy to the standard strain gages and extensometers, and they are also comparable in many aspects from a user's point of view. Indeed, their measurements are local and directional, they require compensation for temperature, they are commonly used bonded onto the surface, although it is also possible to embed the optical fiber in the laminate in the case of composite structures. The main advantages of the FBG over the electrical strain gage are its reliability for long term measurements; because it is frequency coded, without drifting by aging, and its ability for multiplexing; since several FBGs can be engraved on the same fiber at different positions, resulting in the simultaneous measurement points. The most common procedure for multiplexing is to use a different central frequency for each grating, allowing up to ten FBGs in a single optical fiber, for conventional applications. Another multiplexing procedure is to have all the gratings with the same central frequency, with a low reflectivity; if gratings are adequately spaced, the return signal will be time-multiplexed, allowing a much larger number of sensors per fiber. The drawback of this procedure is that its response time is smaller, restricting the system to quasi-static applications.

Getting the strains all along the optical fiber, with adequate spatial resolution and strain accuracy, opens new possibilities for structural tests and for structural health monitoring. This is what is understood as 'distributed sensing', with the main difference that the fiber does not need to have local engraved sensors. Distributed sensing is done by collecting the backscattered radiation occurring at every point of the optical fibre by its natural disturbances, and three different technologies have been developed, related to the wavelength of this backscattered light. In this paper we are using the Rayleigh scattering, or same wavelength as incident light. Further details are given at Ref 1.

1 DISTRIBUTED SENSING FOR STRAIN MEASUREMENTS

The most common application of this technology is just for strain measurements. The distributed sensing technique may significantly improve the instrumentation of structural tests; instead of bonding a large number of sensors, it will be substituted by bonding one (or several) optical fiber at the region of interest. The main advantage of this technology is that it provides a full coverage of the instrumented area. This issue is of special interest in composite structures, commonly designed with changes of thickness and different stacking sequences. As a consequence, the strain field is not uniform and it is cumbersome to monitor all the critical areas with point strain gauges, since this information is directly obtained with distributed sensing. This technology is also very suitable for detecting local buckling, a problem which presents a great level of difficulty when predicting its character. This technique is already used for structural tests of wind turbine blades. Wind turbine blades are the perfect candidates due to their enormous size, because a high number of sensors is required to cover the full structure and the material, with continuous changes of thickness and non uniform properties.

2 DAMAGE DETECTION FROM STRAIN MEASUREMENTS

SHM is defined as the process of acquiring and analyzing data from on-board sensors to evaluate the health of a structure [2]. Damages are local cracks that will act as the failure initiation point, but do not change strongly the overall strain field, only a few cms around the crack are affected. Fiber optic sensors act primarily as strain sensors, so unless damage happens very close to the sensor location, damage may easily go undetected. Several articles were written on the changes in the shape of the spectral peak of an embedded FBG as consequence of cracks happening on top of the fiber, but these are not realistic structural damage cases. To highlight the situation, at figure 1 it is shown the damage done in a composite laminate by an impact, the surface had a bonded optical fibre only 40 mm away from the damage. The permanent strains at the optical fibre were not changed after the impact, and consequently this significant damage would not be detected by the OF. Only when the impact happened closer (10 mm), it produces a change in the strain field of the fibre that would then be detected. It is unconceivable to cover the whole surface of the aircraft with optical fibres, so some procedures have to be developed for doing damage predictions from strain measurements (at figure 2 the readings of residual strains after the impacts are given).

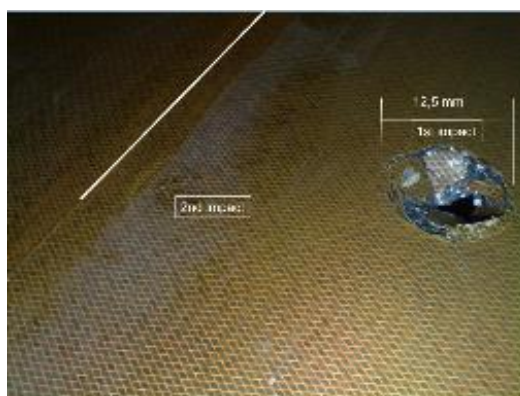


Figure 1. Damage detection from strain measurements is only possible when damage changes the strain field at the sensor

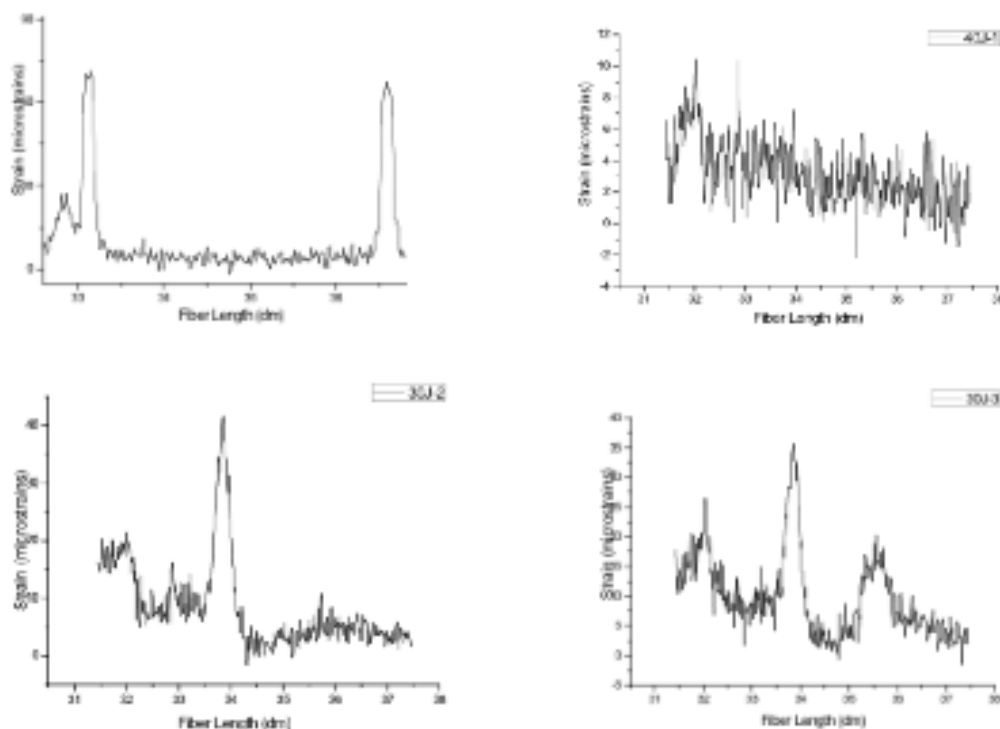


Figure 2. Strains along the optical fibre. Upper left: Local temp increase by two fingers, for localization. Upper right: Residual strains after a 40 J impact, 40 mm away from the fibre. Lower left: residual strains after a impact 30 J, 10 mm away form the fibre. Lower right: Strains after a second impact of 30 J

Looking at the physical damage done in the laminate (figure 1), the 40 Joules impact was strong enough to penetrate the laminate, but it did not caused a change in the strains 40 mm away. The other two impacts of 30 Joules only produced a barely visible indentation at the laminate, and a permanent change in the residual strains, affecting a zone 20 mm around the impacts.

Currently, three main approaches for detecting damage from strain measurements are being investigated:

- 1) High resolution fibre optic distributed sensing (OFDR Rayleigh scattering), presented in this paper.
- 2) Strain mapping with a dense network of sensors. Statistical analysis tools, like PCA, have been successfully used. Presented at this Conference in a companion paper [3]
- 3) Hybrid FBG/PZT systems. FBGs used to detect the ultrasonic elastic waves [4, 5]

Damage detection with FBG by changes in the spectral peak is described at [6], and a review of techniques for civil and aeronautics applications is given at the books [7] and [8], respectively.

2.1 Detecting a delamination in a flat laminate.

Strain changes induced by a delamination caused by an impact are related to the residual strains built in the laminate during the curing and have only a local influence, limited to the delamination area. For these reasons a high-density strain sensor network is required, and formerly SHM techniques for delamination detection were not based on strain measurements.

To study the changes in the strain field promoted by impact damages, plates 150 mm long and 100 mm wide were manufactured with an embedded optical fiber. Plates were built with carbon/epoxy tape AS4/8552 with $[0_2,90_2,0_2]$ cross ply lay-up. Optical fibers were embedded along the longitudinal central line between plies with the same orientation. The embedded optical fiber has polyimide coating with a final diameter of $140\pm 2 \mu\text{m}$. This type of coating is recommended for measuring the strain gradients due to their small thickness.

The first plate was subject to a 2.4 J impact at the middle of the plate. With this energy level, fiber C-1 (embedded in the opposite side to the impact) was broken. The strain readings at the other two fibers show a peak in damage location with similar strain level. In Figure 3 the ultrasonic C-Scan inspection after the damage can be observed. The strain field is mainly affected in the delamination area, with a maximum of nearly $500 \mu\epsilon$. The fibre embedded in the middle of the plate, between the 90° plies, presents a strain field variation limited to the delamination area. With an impact of 4.4 J, all the fibers were broken. Test performed with fibers with acrylate coating of $250 \mu\text{m}$ did not show an improvement of resistance to impacts.

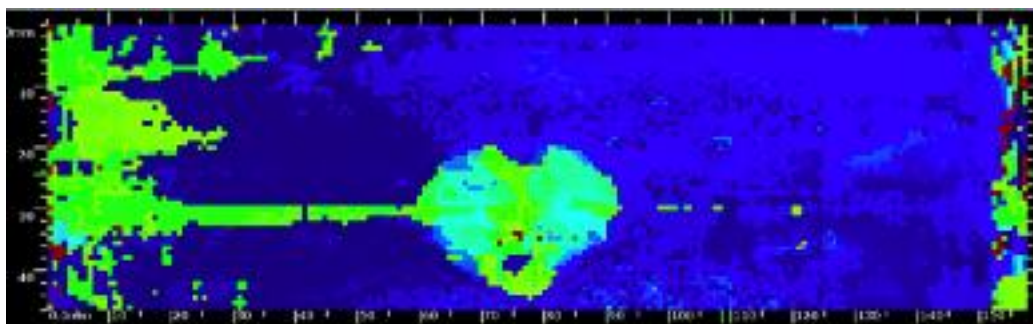


Figure 3: Ultrasonic inspection C-Scan after 2.4 J impact

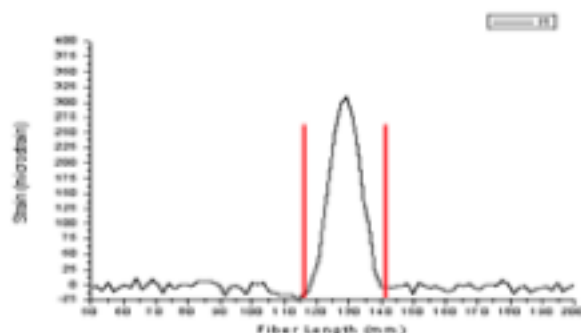


Figure 4. Measurements of the residual strains after the impact with optical fibers

2.2 Mapping the delamination in a flat laminate.

Strain measurements obtained from the total surface can be used to create a strain map of the structure. In case that damage have promoted a change in the strain field, it is possible to obtain an image that represents the state of the structure. Figure 6 shows the effect of a delamination in a cross ply laminate of 200x200 mm. Strain data was obtained from a fiber in a crooked configuration that covered one of the sides.

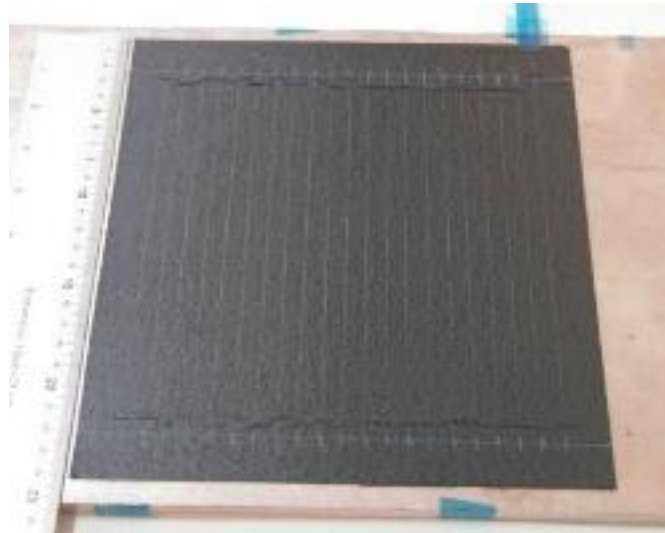


Figure 5: Optical fiber to be embedded with a crooked path in a composite laminate

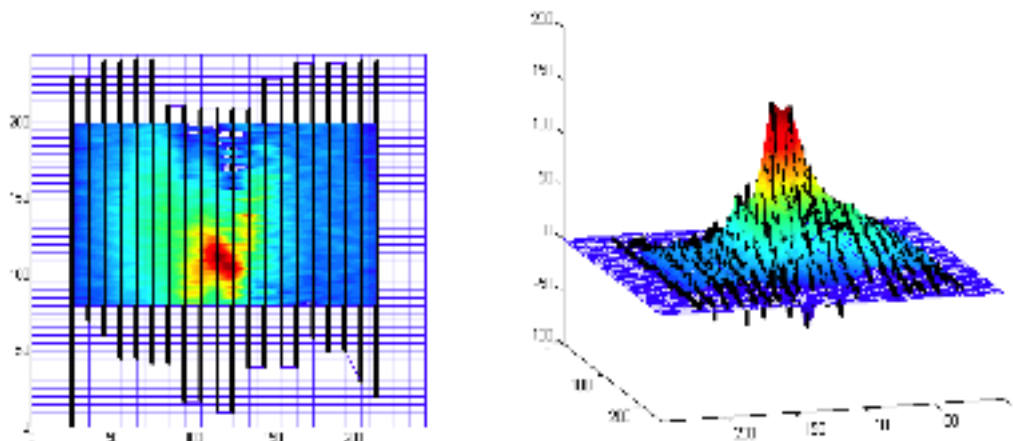


Figure 6: Strain map due to a delamination in 2D (left), and 3D (right)

2.3 Monitoring the stringer run-away in composites structures.

Most of the aeronautical structures are built as stiffened panels and shells, usually by a cobonding process for composite materials (skin is uncured, stiffener are added as cured rigid elements). This is an efficient way to achieve a very high level of structural integration, but still an issue is unsolved: the stiffener run-away, or debonding starting at the tip. Classical way to solve it is by increasing the foot size (which makes more expensive the manufacturing of the stiffener), and by ‘chicken rivets’. Nevertheless, it needs to be inspected in service, so an automated procedure to check the structural integrity is highly desirable. At the European project SARISTU (Smart Aircraft Structures) an activity is carried out to solve this issue, with twodifferent approaches: A) Distortion of the spectral shape of embedded FBGs. B) Fibre optic distributed sensing.

A flat laminate with an embedded optical fibre, similar to the one presented at figure 4, was prepared, the stiffener was added and the whole set was cured (fig 7, left). To promote a progressive debonding, a mechanical artifact was attached (fig 7 right). With the screw, the crack was grown, then unloaded again.

The occurrence of the crack has locally changed the strain state at the flat laminate, as measured by the embedded fibre and plotted at figure 8, left. The debonding has created an area of compressive strains just below the stringer, the maximum value not very high (-80 MPa), but clearly detectable. The crack front is clearly defined, and it is coincident with the findings obtained by ultrasonic inspection (figure 8, right). Similar results are obtained at every step of the crack growth, which demonstrates the reliability of the technique.

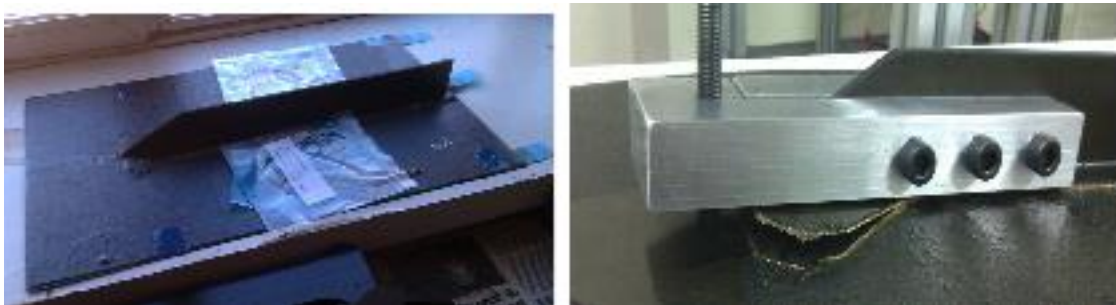


Figure 7 Manufacturing a cobonded stiffened panel with an embedded optical fibre (left), and artifact to promote a progressive debonding (right).

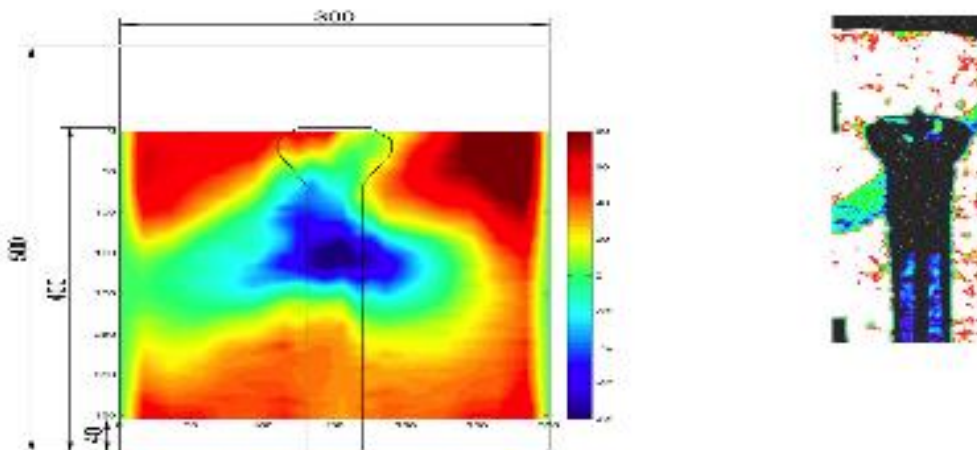


Figure 8 Map of the strains (left) and C-Scan image of the ultrasonic inspection (right)

2.4 Monitoring stiffener debonding by impacts on an aircraft structure.

Figure 9 shows a part of a real aircraft structure, done in CFRP. An optical fibre was bonded at the internal surface, with loops of radii higher than 2 cm, to avoid optical losses. A BVID (Barely Visible Impact Damage) was done on the external surface, just below the stiffener foot, at the positions marked with dotted white spots; occurrence of a delamination was verified by ultrasounds, figure 10 (right) shows the B-Scan of the area, the debonding of the stiffener foot is seen as a intermediate green line. On figure 10 (right) the change in the strain field is plotted, always for the unloaded structure, identifying the area were the impact was given.



Figure 9 Cured CFRP structure, with bonded optical fibre

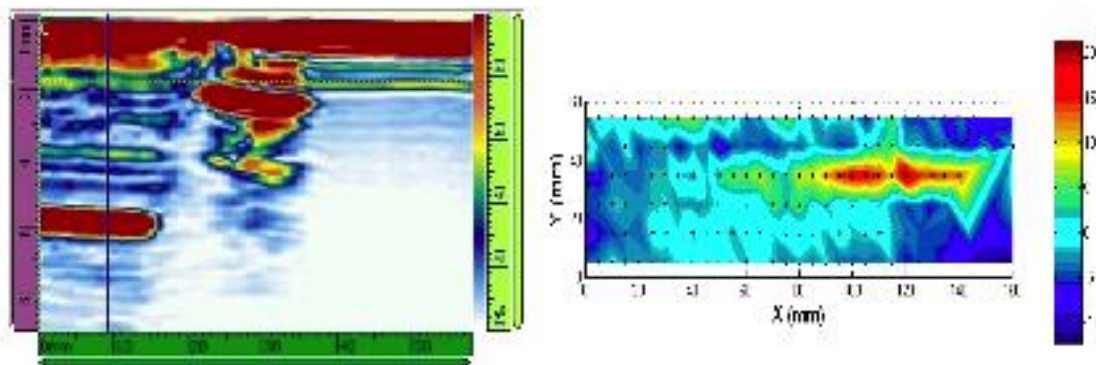


Figure 10 Map of the strains (left) and C-Scan image of the ultrasonic inspection (right)

CONCLUSIONS

While FBG is useful for local strain measurements, similarly to strain gages, new possibilities are opened by the distributed sensing, giving the information all along the optical fibre. Structural tests may be instrumented with greater details, and crack occurrence will be easily detected, as long as the crack crosses the optical fiber path.

The changes in the strains are very intense at the tip of the cracks, but smooth out very quickly, a few cms away the changes are negligible, so it is very difficult to get information on damage occurrence just from strain measurements; Fibre optic sensors are just strain sensors, so its usage for damage detection is very limited, still under development. Currently, three main approaches for detecting damage from strain measurements are being investigated:

- 1) High resolution fibre optic distributed sensing (OFDR Rayleigh scattering). When the crack crosses the optical fibre, a high strain spot is detected. This technique is applicable to cover high risk areas, like stiffeners debonding.
- 2) Strain mapping with a dense network of sensors, either distributed OF or highly multiplexed FBGS. Multivariate statistical analysis tools, like PCA, is needed to extract the meaningful deviations, and to distinguish damages from loads or environmental factors changes.
- 3) Hybrid FBG/PZT systems. FBGs must detect the ultrasonic elastic waves, high sensitive and high speed interrogation systems are then required.

ACKNOWLEDGEMENTS

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