Fiber optic sensors for SHM of bonded repairs in composite structures

ALFREDO GUEMES

ABSTRACT:

Structural Health Monitoring (SHM) claims to be an alternative way to perform non-destructive inspection of structures, saving costs and time, and increasing the reliability over conventional non-destructive inspection methods. Health monitoring of bonded repairs provides a localized application for applying the state of the art of health monitoring technology. Many bonded repairs are in service on flying aircrafts. However, due to the uncertainty of long term adhesive performance and the inability to continuously assess the repair condition, current design practices are inherently highly conservative, and the number of applicable situations is limited. A system which may continuously validate the quality of adhesive repairs would be very desirable.
This article review what has been done up to now, and show the results from a recent experimental program, highlighting the difficulties to overcome before a wider usage.

INTRODUCTION

The Structural Health Monitoring (SHM) of repairs in composite structures is receiving a significant attention among the SHM practitioners; according to EI Compendex database, about 25 new papers appears each year on this topic. This interest is well justified. It is a clear request to the SHM specialists by the structural engineers, and the solution of this problem would help to build up their confidence on these new techniques. Secondly, and it has been the main emphasis for this work, SHM technologies seems to be the most feasible approach to assess in service the quality of a bonded repair, which is an important requirement, having in mind that repairs may need be done at remote places and with less resources than in the aircraft factory.

Many authors have already emphasized the benefits of bonded repairs, compared to the traditional bolted repairs, still often required for high responsibility structures. The uncertainties of long term adhesive performances, and the low robustness of the bonding process, sensitive to contamination, moisture in the laminate, deviations in the cure cycle, and many other factors, introduce severe limitations to its applicability. A permanent sensing system, built-in with the repair, able to monitor the condition of the repair in real time, or able to perform the structural check by an automated procedure during the ground times of the aircraft, would increase considerably the applicability of bonded repairs.

Universidad Politecnica de Madrid, Dpt Aeronautics.
3, Plaza Cardenal Cisneros. Madrid 28040 SPAIN
aguemes@aero.upm.es

Papers on SHM for bonded repairs may be classified first by the sensing technique, either piezoelectric wafers or fiber optic sensors (FOS). The piezoelectric approach has achieved a good level of maturity, including in flight demonstration of a repair patch monitored by a Smart layer, done on a F-16 aircraft [1], now under evaluation. Among the FOS group, there are three main approaches:

A) Articles dealing with 'smart patches', or repairs done with composite materials cured in-situ on a cracked metal surface [2 to 4]. This way of repairing has been found very effective; integrating an optical fiber with strain sensors during the repair is straightforward, and research is now focussed on getting information on the crack growth and patch debonding.
B) A group called 'differential strains', which compare the readings from two closely located strain sensors, at the parent structure and at the repair patch respectively [5]. It has been found a reliable technique to monitor the integrity of the repairs; any debonding would change the local strain field from the otherwise very similar readings. The main limitation is the local character of the perturbation produced by the incipient crack, the sensors position must be carefully selected at the failure initiation point. Some results with this approach are discussed later in this paper.
C) Analysis of the spectral information of a FBG (Fiber Bragg Grating) embedded in the bondline. This approach has been explored by the University of Tokyo [6], among others. The concept is that the complex strain field around the sensor promotes a distortion in the reflection spectrum of the FBG, and that any new crack changing the stress field would change also the spectrum. We start discussing first this approach.

EMBEDDED FBG IN STEPPED LAP BONDED JOINTS

A large experimental program for evaluating the feasibility for monitoring bonded repairs by fiber optic sensors is being carried out by University of Madrid together with Airbus Spain. The first phase, recently finished, included lap bonded joints with an array of embedded sensors. Second phase must include conventional repairs done according Structural Repairs Manual.

Experimental Program. Specimen's definition

Stepped lap bonded joints were prepared according AITM 1-0029. The parent laminate was done with eight plies of graphite/epoxy prepreg plain fabric, with a lay-up (0,+45, 90, -45)S. After standard cure and ultrasonic inspection, a stepped lap joint was prepared by sanding the laminate to the dimensions given at fig. 1, followed by water cleaning and drying the laminate for 90 minutes at 120 ºC. An adhesive film layer (EA-9695) was placed at the interface, and identical lay-up was repeated at the repair side, with the adequate overlapping, with the recommended repair material (M20/G0904 from Hexcel). The optical fibers, with five FBG sensors each, engraved at well defined position, were placed over the adhesive film, at the bondline (figure 2). To enhance its sensitivity to transversal stresses, no recoating was done to the FBGs. The vacuum bag was set, and the repair was cured with an Airbus qualified repair system (Sicoteva).

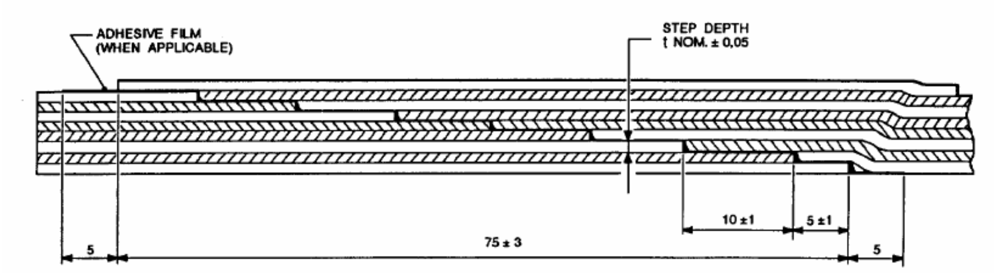


Figure 1. Step-lap bonded joint according to AITM 1-0029

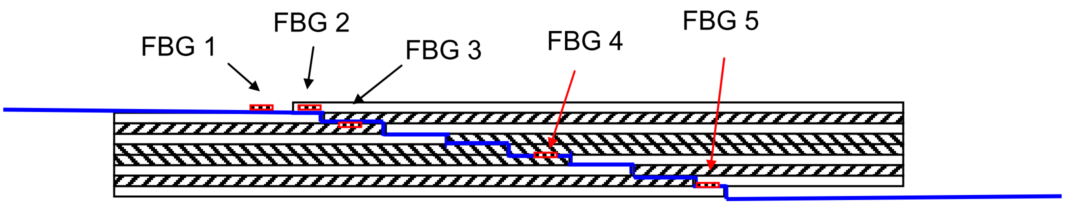


Figure 2. Position of the FBGs inside the bondline

Being a main objective for this work to discriminate among good and defective repairs, five different plates, with 10 specimens each, were prepared under the following conditions:

T1. Reference specimens, the repair procedure defined at the SRM was strictly followed
T2. Same as before, but including FOS
T3. Including artificial defects as small Teflon discs (3 X 3 mm and 10 X 10 mm)
T4. Inadequate cleaning
T5. Insufficient vacuum during the curing (200 mm Hg instead established 500 mm Hg)

At the static tensile tests, the reference specimens failed at loads between 11,9 to 12,5 kN (230 to 250 MPa), always near the first step, in the parent laminate. A crack progressing in the repair area usually appeared, but outside the bondline. Under tensile fatigue loads (max 10 kN, R=0,1), the specimens failed after 20000- 50000 cycles. No significant differences in failure loads were found among T1 and T2 specimens.

Factors influencing the reflected spectrum

The figure 3 shows the original spectrum; FBG 1 was not embedded in the bondline, to serve as temperature sensor during the cure of the patch. Later on, it was bonded with cianoacrylate to the parent laminate. The peaks displace with the applied load, fairly linear as expected, without significant differences among them, neither among the reference or the defective specimens (figure 4). There was a significant drop in the height of the reflected peaks (fig. 5) with the applied load, due to microbending at the consecutive steps, because the connector was placed at FBG 1 side (a loss of 3 dB is equivalent to halve the reflected power). After 6 kN, approximately 50 % of the failure load, the spectrum change dramatically, and the peaks after FBG1 decrease near to zero.

Evidence of internal Fabry-Perot effects, associated to fiber breaks, was found by a progressively stronger waviness that masks the embedded FBGs (fig 6)

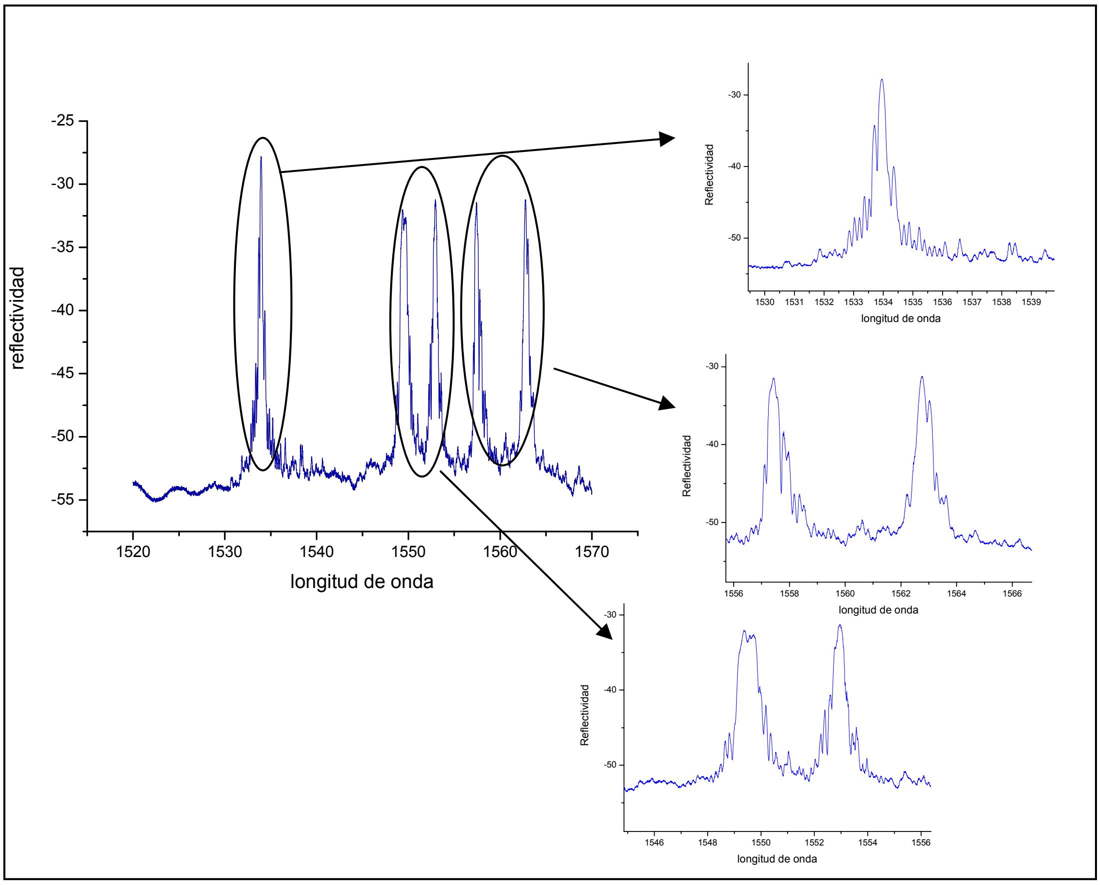


Figure 3.Initial reflection spectrum of the optical fibre

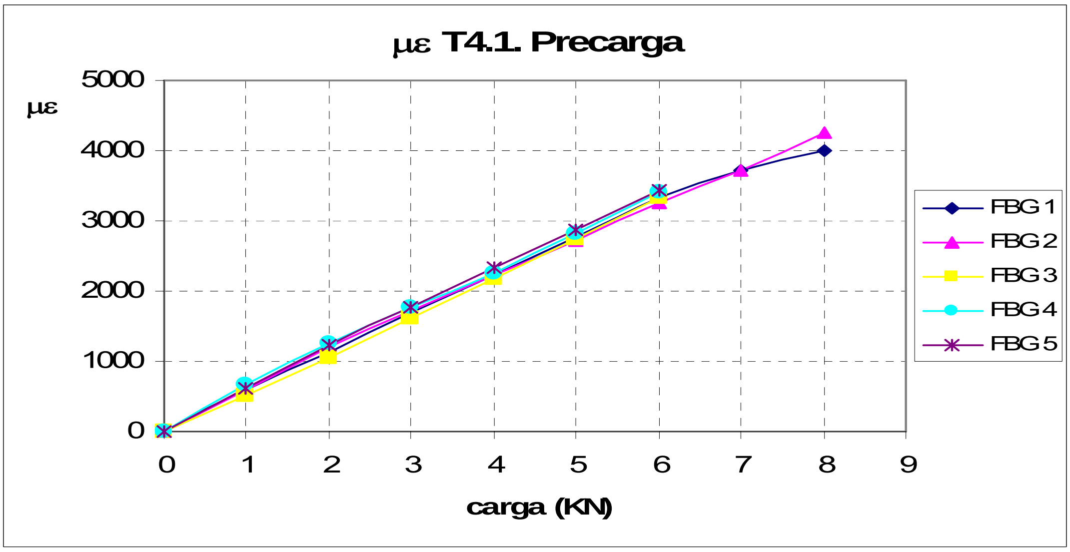


Figure 4. Peak displacements :VS. Tensile Load

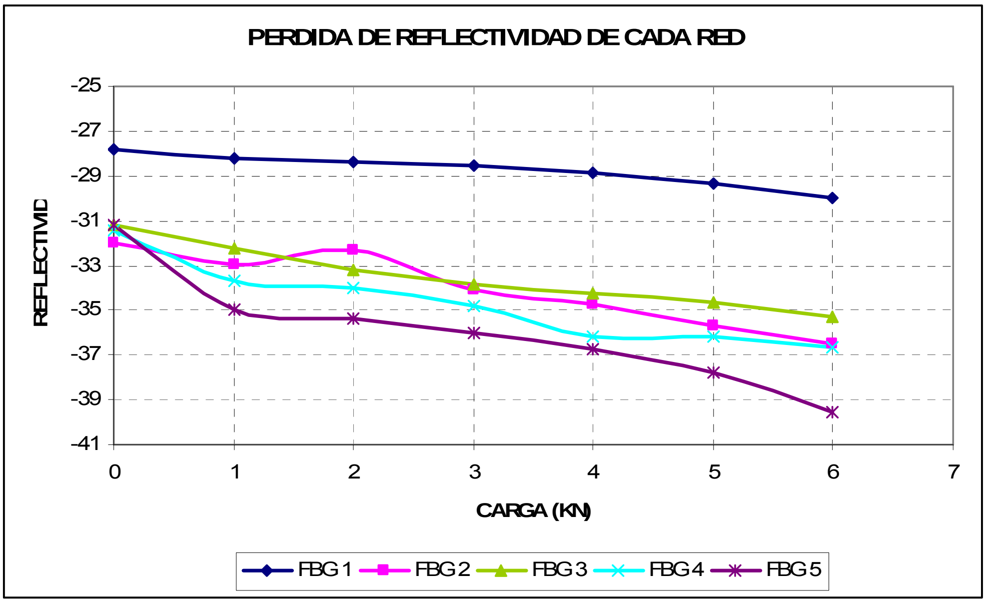


Figure 5. Loss in the reflected power, caused by microbending

These failures in the optical fibers could have been prevented by recoating the fiber after engraving the sensors, so it is not a limiting factor. Important information is contained in the shape of each individual peak, which widens with the applied load, and finally resolves in two distinct peaks at 6 kN (Figure 7). These changes could have been significant for discussing the internal stress field, if other factors which are discussed next were not influencing the results.

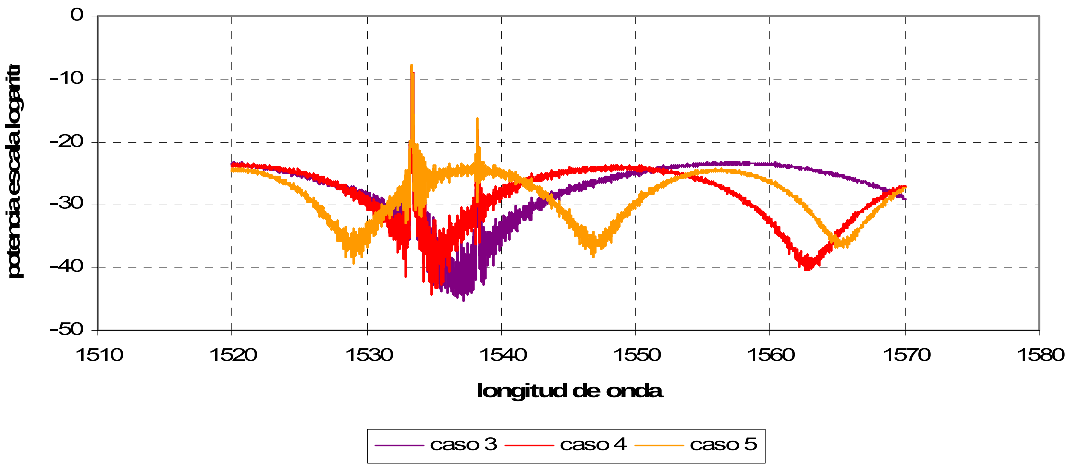


Figure 6. reflection spectrum after internal fiber breaks, with spontaneous F-P

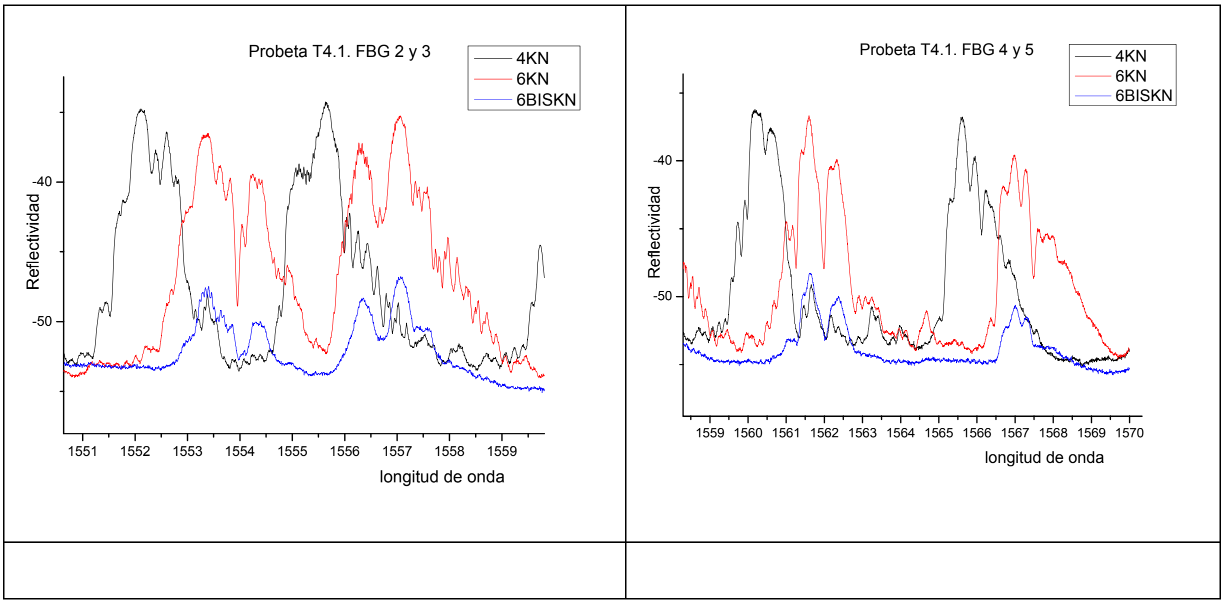


Figure 7. Spectral distortion under loads for embedded gratings

Influence of the composite texture

It has a very significant effect on the spectral response. In our tests, one of the gratings (FBG1) was not embedded, but remained free, and was later bonded at the parent laminate during the mechanical tests by cianoacrylate. Consequently, we could expect a behaviour free of transversal effects, and consequently without distortion of the spectrum. Nevertheless, the experimental finding is a spectral distortion not identical but similar to that shown in figure 7.

To clarify this phenomenon, gratings of different length were cold bonded to the surface of the same laminate, done with fabric (Fig 8). Only the very small grating (2 mm) does not suffer from spectral distortion under load (upper part of figure 9) compared with the strong distortion of the 10 mm grating 5 (lower part of figure 9). Unless these effects can be taken into account this approach seems difficult to apply to composite laminates made out with fabrics, limiting its applicability.

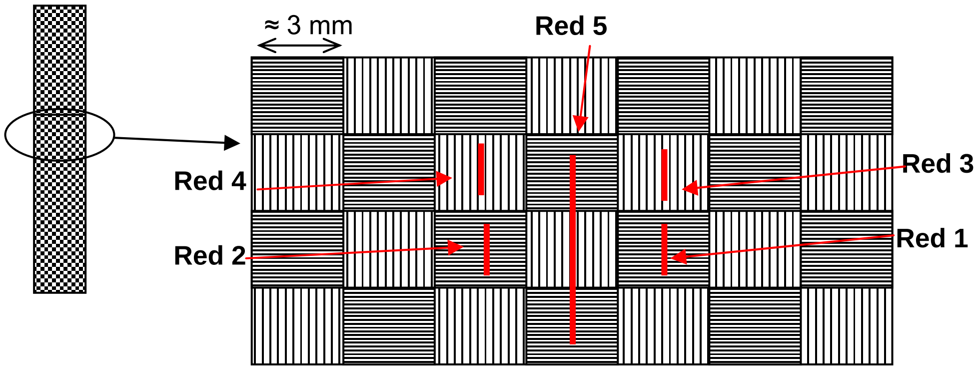


Figure 8. Representation of the fabric, and locations of the bonded gratings.

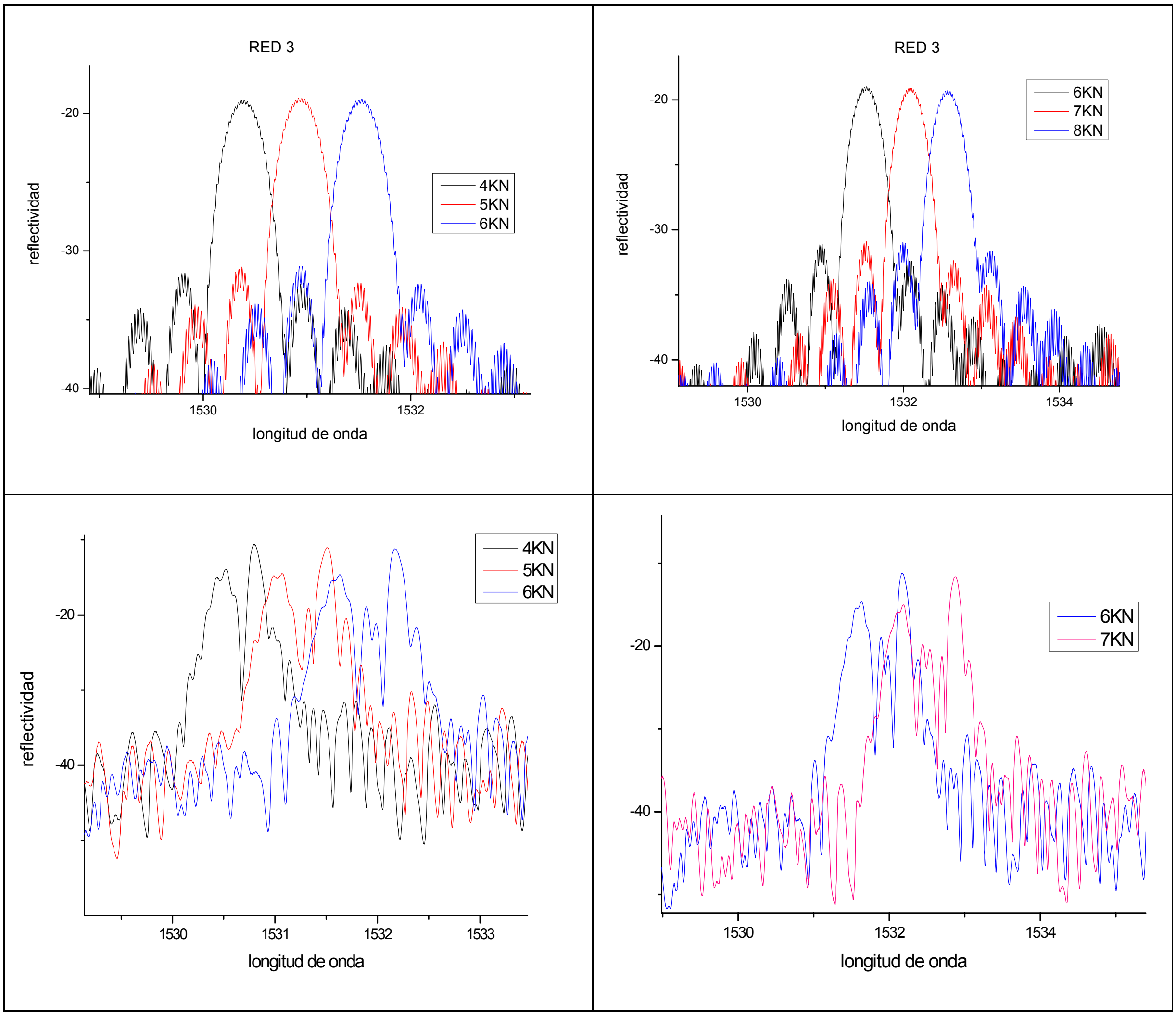
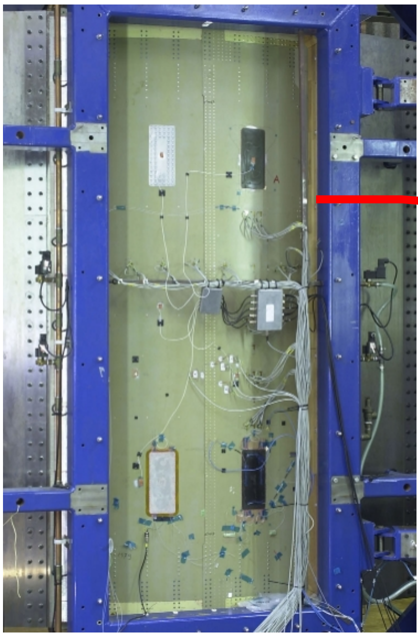


Figure 9. Change of the spectrum with load, for short (2mm) and long (20 mm) gratings.

Strong strain gradients are identified along the FBG 5, corresponding to the changes in the surface of the composite from warp to fill orientations. Very short gratings to avoid this effect suffer from a widening in the pulse shape, and consequently little information could them be obtained from the pulse distortion.

THE DIFERENTIAL STRAIN APPROACH

The concept is to compare the strains in to closely located gratings, one of them bonded onto the patch, while the other remaining in the parent structure. The technique was tested in a composite patch bonded to a GLARE panel, and four pairs of gratings were bonded in parallel positions (see figures 10 and 11).



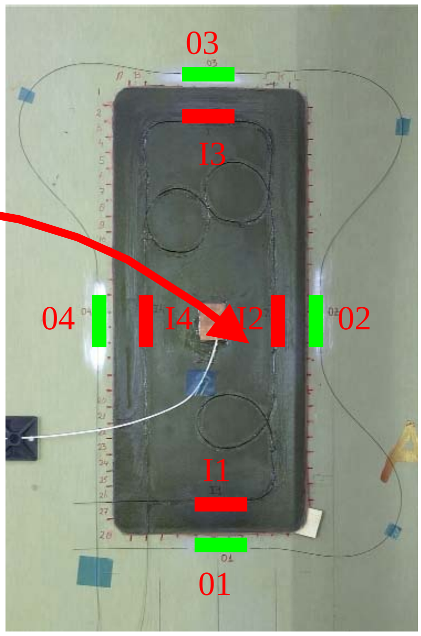


Figure 10. Overall view of the panel with SHM sensors. Figure 11. Bonded composite patch A on the GLARE skin. An AE sensor and the two optical fibres with eight FBGs can be seen.

After a first test series including loading-unloading cycles, damage did not appear at the monitored repair patch, and bonded sensors did not showed significant spectral distortion. After a second test series, a damage event happened (debonding in the right lower corner of the patch); then, measurements at zero load condition was done, and significant results have been obtained. A relative drift of 117,5 με has appeared between the pair of sensors that are closer (2 cm) to the delamination. The pair of sensors FBG2, which were only 10 cm away from the corner did not detect the crack. It is confirmed the local character of the perturbation. The new distributed sensing technique as BOCDA [7], offers an alternative solution to the FBGs to cover the full enveloppe.

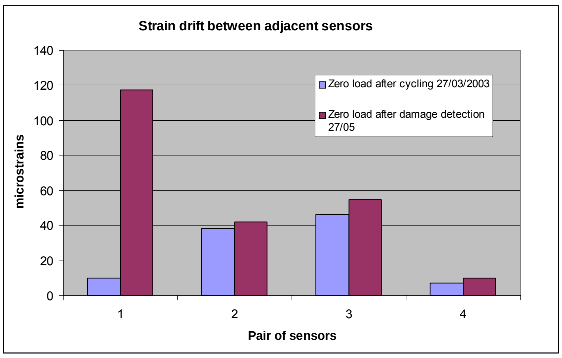


Figure 11. Drift of 117,5 με between the pair of sensors closer to the delamination

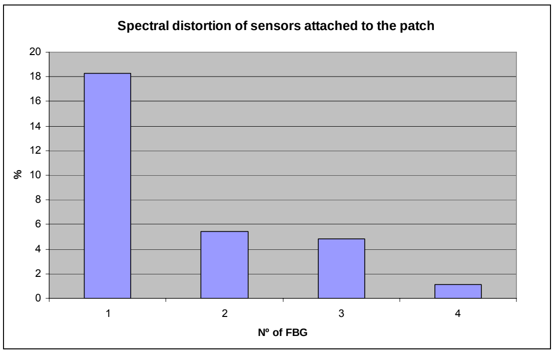


Figure 12. Spectral distortion in the grating bonded on the patch

Additionally, a spectral distortion of 18% has been detected in the FBG I1, the grating bonded in the surface of the patch closer to the debonding. These results seem to confirm the capability of these techniques to detect perturbations in the near stress/strain fields promoted by debondings/delaminations.

CONCLUSIONS

There is a significant interest in the development of SHM systems for bonded repairs. PZT based systems have achieved a good level of maturity. Several fiber optic technologies are promising, the most robust approach is to compare the strain at the bonded patch and the parent structure. The main limitation is that the strain perturbation caused by the crack has a very local range. This can be solved either by a judicious selection of the FBGs location at the corners of the patch, where crack is going to start, or by using the new BOCDA systems for distributed sensing.

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