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REPAIR PATCH MONITORING WITH EMBEDDED OPTICAL SENSORS BY A RESIDUAL STRAIN RELEASE TECHNIQUE

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ABSTRACT

Repair of metal structures with carbon fibre reinforced plastic (CFRP) patches holds a high potential for aeronautic structures. Bonded repairs with CFRP offer the advantage within others to repair in places where a standard riveted repair is not possible due to space limitations or geometrical conditions. It is of vital importance that a bonded repair patch will not peel off during service. Monitoring the patches provides a tool to detect a debond in the repair patch before the debond becomes a critical issue.

A monitoring technique has been studied that enables to detect a patch peel off using fiber optic Bragg grating sensors (FBGSs) embedded in the CFRP-patch. Temperature compensation has been introduced to enable the application of this technique in a wide temperature range. The technique allows the monitoring of the patch on ground after a defined number of flight cycles.

The viability of the monitoring principle was studied and demonstrated on seven specimens made of typical aeronautic aluminum with bonded CFRP patches that are instrumented with two or four embedded FBGS. The results of the tests show that the embedded sensors can indeed sense the debonding of a bonded CFRP patch used to repair an aluminum structure. The sensitivity of the sensors is sufficiently high to detect a crack front that is still 10 mm far from the sensor. The temperature effect on the embedded sensors that monitors the crack front can be compensated by a second sensor that is far from the sensor front.

A robust pre-cured sensor mat design was developed and manufactured. This sensing mat was made using three fibers each with four FBGSs, embedded between two glass fabric plies, providing repeatable, easy and robust sensor integration. Test structures with monitored composite repair patches were designed and manufactured to demonstrate the performance of the sensing mat during fatigue tests under wide temperature range. The change in readings of a low spatial resolution sensor net, in response to the growth of critical defects is significant enough to make a clear indication of patch deterioration with a reduced chance for misinterpretation. It is, therefore, hoped, that the use of such a system will allow a significant increase in the regular inspection intervals of bonded repairs without compromising safety.

KEYWORDS : *Bonded composite patch repair, metalic aircraft structures, SHM, FBGS, strain relese*

INTRODUCTION

Repair of metal structures with carbon fibre reinforced plastic (CFRP) patches has a high potential for aeronautic structures. Bonded repairs with CFRP offer the advantage within others to repair in places where a standard riveted repair is not possible due to space limitations or geometrical conditions. This is of special interest in fighter aircraft structures and helicopters where in many places only a small space is left in-between access holes and riveted components. A bonded repair with composite material patches offers in this cases quite often the only solution to repair instead of replacing the entire structure, as stated Baker *et al*. for the repair of a cracked lower wing panel of a F-111 fighter aircraft [1] and [2]. Successful bonded patch repairs have also been performed by some of us on a F-16 fuselage structure where no other repair was reasonable due to space limitations [3]. Bonded composite patches are a very good option for primary structural repair but require that the bonded repair patch will not peel off during service. Once it only partially peels of, the repair loses its efficiency and the crack under the repair can grow very fast up to a possible catastrophic failure as Dorfman *et al*., stated in [4].

Inspections of the repair patches directly after the patch bonding cannot guarantee a perfect patch performance along its service life, because a bad bonded patch (weak or kiss bondings) is practically no detectable with standard NDI techniques and harsh environmental conditions can weaken the bonding. Periodic inspection of the debonding during service life using ultrasonic techniques are normally scheduled according to worst case scenarios of patch deterioration and are due to this fact more frequent than necessary which makes them costly and time consuming.

Monitoring the patches with integrated sensors provides a useful tool to detect a debond in the repair patch before it becomes a critical issue. The technique can be performed on ground and is fast and inexpensive. Fibre optic sensors seem to be the best choice for the monitoring of the quite often thin patches due to their minimal dimensions and multiplexing capability that enable to monitor the entire patch with several integrated sensors but having only a tiny less than 1 mm in diameter cable that egresses the patch. The same sensors that are used for the debond monitoring can be used for tracking a possible crack growth under the patch when load is applied.

The following paper describes a technique for composite patch debond monitoring for the repair of metallic structures based on the strain release of the debonded patch areas using integrated FBGSs. The technique has been characterized on specimen level. Finite element models have shown a good agreement with experimental results.

A robust pre-cured sensor mat design was developed and manufactured. This sensing mat was made using four fibers each with three FBGSs, embedded between two glass fabric plies, providing repeatable, easy and robust sensor integration. Test structures with monitored composite repair patches were designed and manufactured to demonstrate the performance of the sensing mat during fatigue tests in a wide temperature range. The change in readings of a low spatial resolution sensor net, in response to the growth of critical defects is significant enough to make a clear indication of patch deterioration with a reduced chance for misinterpretation. It is, therefore, hoped, that the use of such a system will allow a significant increase in the regular inspection intervals of bonded repairs without compromising safety.

1 SIMPLE SAMPLE SPECIMENS

The specimens are made of two materials, of aeronautic 2024 T3 aluminum that represents the stiff aircraft structure and of a 1 mm thick CFRP layer with quasi isotropic stacking sequence that represents the repair patch. High thermal induced residual strains of about -1400 με are introduced during the 120ºC hot bonding process between both materials due to the different thermal expansion coefficients of the CFRP and the aluminum. These residual strains are released when a debonding of the CFRP patch happens. The change of the residual strains provokes an expansion of the CFRP patch material and hence a measurable strain in the embedded FBGS located near the edge. The FBGS in the middle of the specimen far to the edge delamination allows a thermal compensation of the near the edge located FBGS.

An initial delamination provoked by a release film located between the CFRP-patch and the aluminum tube enables to initiate the delamination for the mode-I tests. Three different configurations of delamination lengths have been prepared to simulate the advance of the delamination. The first delamination is 25 mm from the edge of the specimen and is still ’far’ from the FBGS whose center is located at 65 mm from the edge. No strain gradients are expected, so that the sensors still measure the full thermoelastic residual strain of -1400 με calculated by a finite element model, FEM. In the second and third configuration, a 40 mm and a 50 mm long delamination came nearer to the sensor and a release of the residual strain is expected. Marks have been inscribed in the specimen lateral sides for easier identification of the crack advance.

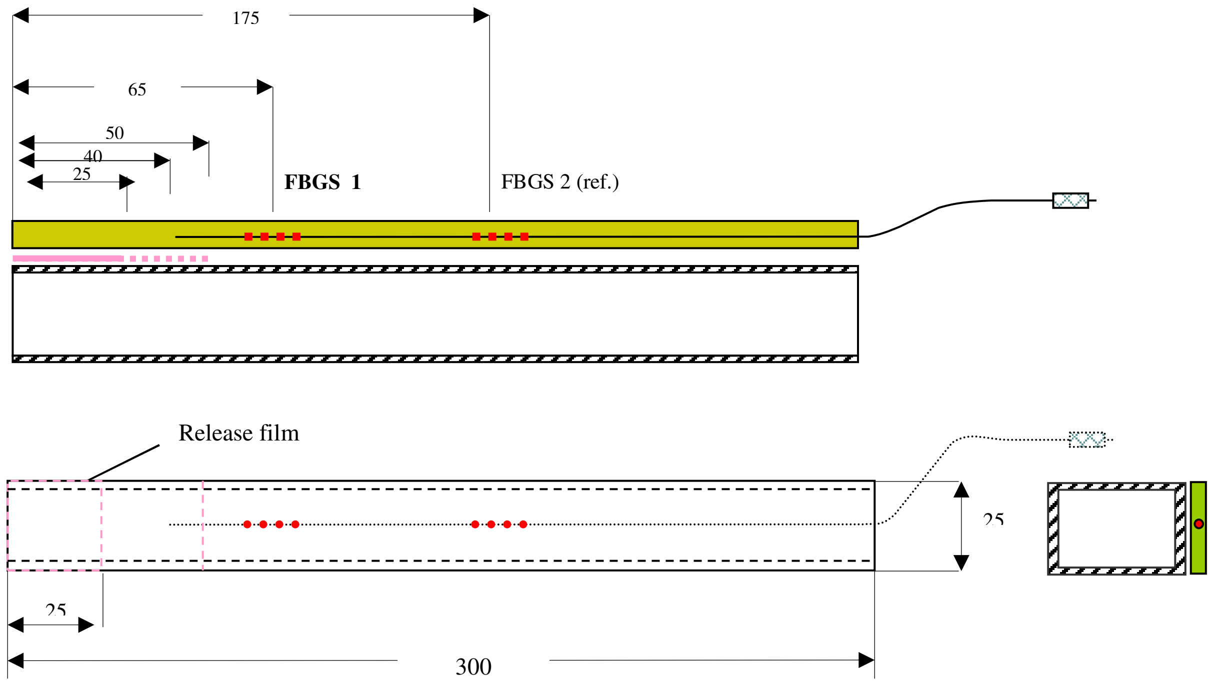

Figure 1: Simple specimen design with three delamination lengths of 25, 40 and 50 mm. The red dots represent the position of the FBGSs

1.1 FEM of a simple sample specimen

Two types of Finite Element Models (FEM) have been prepared:

1. Residual strain ε_0 in the sample, generated by the curing of composite patch on the aluminum structure (tube).
2. Analysis of progressive delamination in the sample

The 1st FEM is prepared by using PATRAN as Pre/post and NASTRAN (linear solution) as solver. The aim of this FEM is to calculate the residual strain ε_0 in the sample, generated by the curing of composite patch on the aluminum structure (tube), as a function of the debonding length. The residual strain is produced during the 120ºC curing by the different thermal expansion coefficients of the aluminum tube ($\alpha_{Al} = 24 \cdot 10^{-6}$ 1/K) and the CFRP patch ($\alpha_{CFRP} = 3 \cdot 10^{-6}$ 1/K), and it can be measured experimentally by the FBGS sensors.
The objective is to prove that when the debonding grows, the residual strain is progressively released, therefore FBGSs can be used to monitor the health of the repair, or in other words FBGS can be used to detect debonding growth before it gets critical. In figure 2 the FE residual strain at sensor layer is shown for a debonding length of 25 mm. The residual strain well inside the CFRP patch is around -1430 με, this level decreases when approaching the debonding edge (becomes almost cero). At the FBG sensor position the residual strain change or drop is measurable. This FE analysis is useful to correlate mechanical tests performed on samples with different debonding lengths, and measuring residual strain with no load applied. The 2nd FEM is quite similar to the 1st

one regarding the type of elements, mesh size, etc., but has a different objective that is to simulate the progressive debonding in the sample when applying mode I loads. For that, cohesive elements (CZ) were used for the adhesive and the FEM Solver is MARC (non – linear implicit).

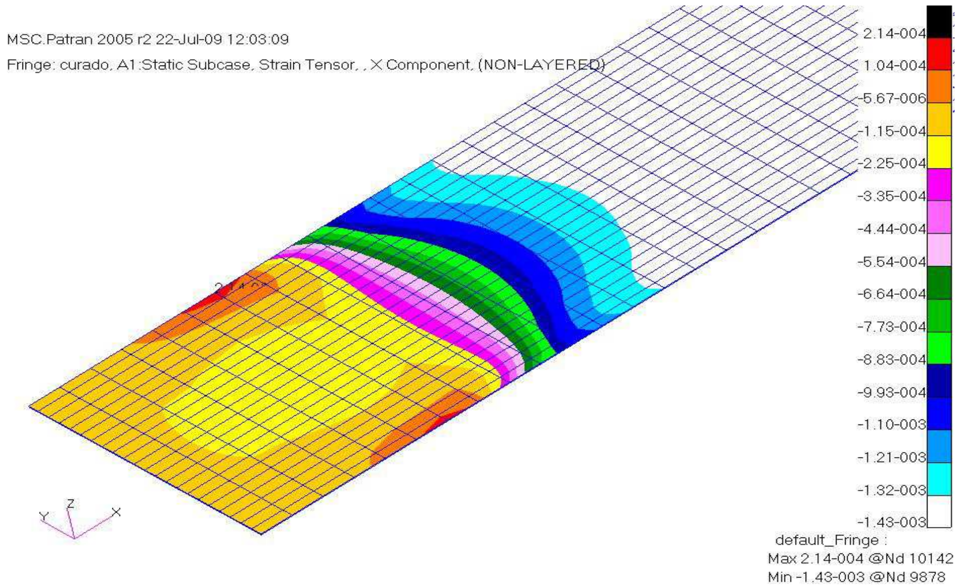

Figure 2: Residual strain in sensor layer for a debonding length of 25 mm.

1.2 Test set up and procedure

The specimens have been tested in a universal testing machine from INSTRON type 5583. To open the initial delamination under mode-I, load has been introduced in the specimen by means of "T-shaped" attachments screwed tight to the specimen edges, as can be seen in figure 3.

The metal squares are introduced in bearings of pull rods of the testing machine. Due to the bearings no bending moments are introduced in the specimens during the mode I tests. A load cell measured the tensile load during test. A type K thermocouple has been attached to the specimens to register the specimen temperature and compare the results with the second FBGSs that are far from the delamination and are used for temperature compensation. The machine opened the crack at a constant pull speed of 2 mm/min. The machine was stopped and the crack length was measured with a digital caliber when the crack has advanced between 1,5 mm to 5 mm. The measurement has been performed on both specimens' lateral sides by visual inspection using magnifier glasses. It was necessary to measure on both sides of the specimen because the crack front was not perpendicular to its length axis, but inclined by an angle of about 10º. Consequently, the crack length was determined as the mean of both measured values.

1.3 Test results and comparison with FE analysis

The residual strain releases in all the specimens with the increment of the crack length show good agreement with the FEM result (1st one, linear NASTRAN FEM). The closer the crack to sensor location the steeper is the slope of the graph, figure 4. At 10 mm to the sensor, about 100 microstrain are already released, and the debonding can be predicted using a standard FBGS lecture equipment. It has been shown that comparable results are obtained when the delamination length is initially longer, as in the case of the specimens 2 and 5 (40mm) and 3 (50mm) or if the delamination has been opened from the ºshorter initial 25 mm and has reached these values of 40 and 50 mm, respectively, after opening the crack.

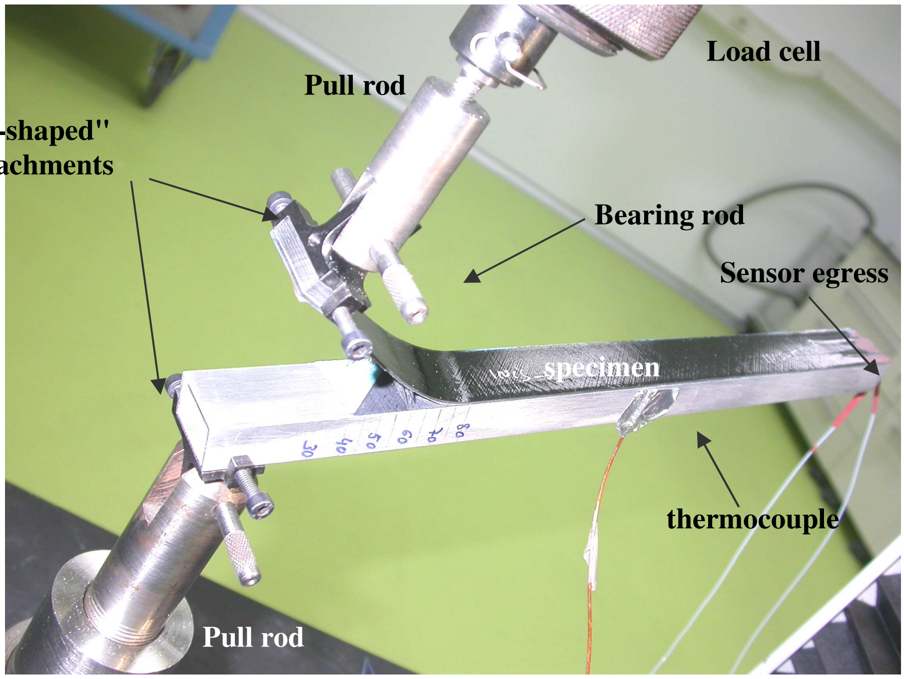

Figure 3: Specimens during test

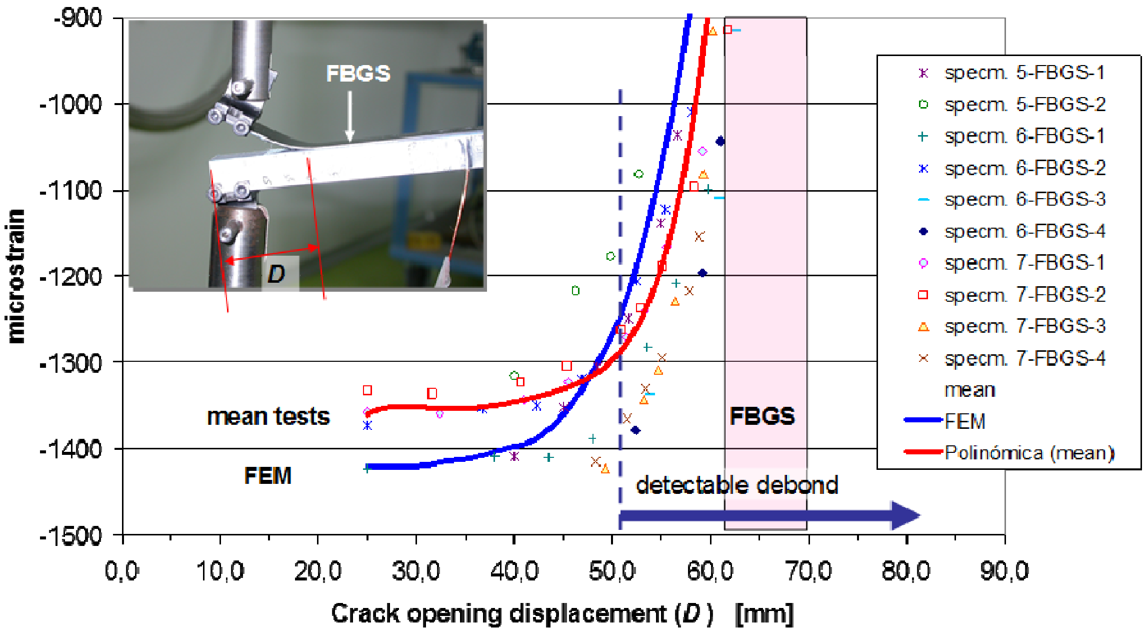

Figure 4: Test results of strain read by FBGSs of three specimens all measured without load applied during wavelength measurement, and comparison with FEM results. The red line shows the regression curve of the mean values of the measured results.

Correlation of the 2nd FEM (non-linear in MARC) is more difficult because CZ elements do not support thermo-elastic strains, therefore FEM results have to be calculated by two separated parts: thermo-elastic strains plus mechanical strains. In general FEMs results (strain read by FBGS) are coherent, and show a quite similar behavior to the experimental measures with load applied while measuring FBGS strains. The general conclusion is that the CZ FEM methodology used seems adequate, and predicts quite accurately the behavior, and the progressive debonding, of loaded samples

The results of the tests show that the embedded sensors can be relied upon for measuring the debonding of a bonded CFRP patch used to repair an aluminum structure. The sensitivity of the sensors is sufficiently high to detect a crack front that is still 10 mm far from the sensor. The temperature effect on the embedded sensors that monitors the crack front can be compensated by a second sensor that is far from the sensor front. The FE model showed a good agreement with the measured results.

The obtained results from the mode-I tests justified the manufacturing of structural demonstrators to proof the results in condition similar to in service conditions of aircraft structures.

2 TECHNOLOGICAL DEMONSTRATORS

In the simple sample tests it has been shown that the delamination of a repair patch can be detected before it becomes a critical issue. These tests have been performed with representative aeronautic materials but with small specimens and in quasi static tests at room temperature. The technological demonstrators should show that repair patch monitoring is also possible in conditions more close to real aircraft structures conditions that means in larger structures, fatigue loads and a wide temperature range from -55 ºC to 100 ºC.

2.1 Demonstrator design

An instrumented demonstrator has been manufactured and tested. The demonstrator is composed of a CFRP patch on each side with embedded FBGSs, co-bonded on a typically aeronautic 7075 T7351 aluminum plate with a crack just under the center of both patches, figure 5. The FBGS are pre-embedded in a sensing mat with rugged fiber egress to enable reliable sensor integration even in field conditions. Each sensing mat has four fibers and every fiber is equipped with three FBGSs. An initial debond was artificially created between the CFRP-patch and the aluminum plate. The debond size was 25mm in accordance to the simple specimen tests that were performed. The demonstrator was submitted to fatigue tension loads and different environmental conditions in order to propagate the debonds.

One side the surface of the aluminum plate was treated with a standard phosphoric acid anodization (PAA) surface preparation for good adherence between the patch and the aluminum surface. The other side was treated only with abrasion in order to facilitate the debond growth.

2.2 Demonstrator tests

Tensile fatigue tests have been performed with a load spectrum of 0 to 3 tons. The tests have been performed at different temperatures to create test conditions that would facilitate a patch debond:

- 100k cycles at RT
- 100k cycles at -55ºC
- 100k cycles at 80ºC
- 100k cycles at 100ºC

The rupture of the panel took place at 400k cycles during the fatigue loading. No significant difference was observed during the tests between the residual strain in the good bonded patch and in the poor bonded patch. Also, no significant difference was observed between FBGSs which were close to the debond, but still more than 10 mm away and those which were far from it. During the fatigue tests the patches on both sides did not debond although the crack was growing slowly under the patches which demonstrates the good quality of the bonded patch. The integrated FBGSs were used during the tests to monitor the crack growth. The distributions of the loads are changing in the panel when the crack is growing and sensor close to the crack front are exposed to higher strains and strain gradients. Typical demonstrator FBG readings during the last phase of the fatigue tests are shown in figure 6. The slow but steady stain increase, induced by the growing crack as demonstrated in this experiment, gives enough time for taking corrective action before failure.

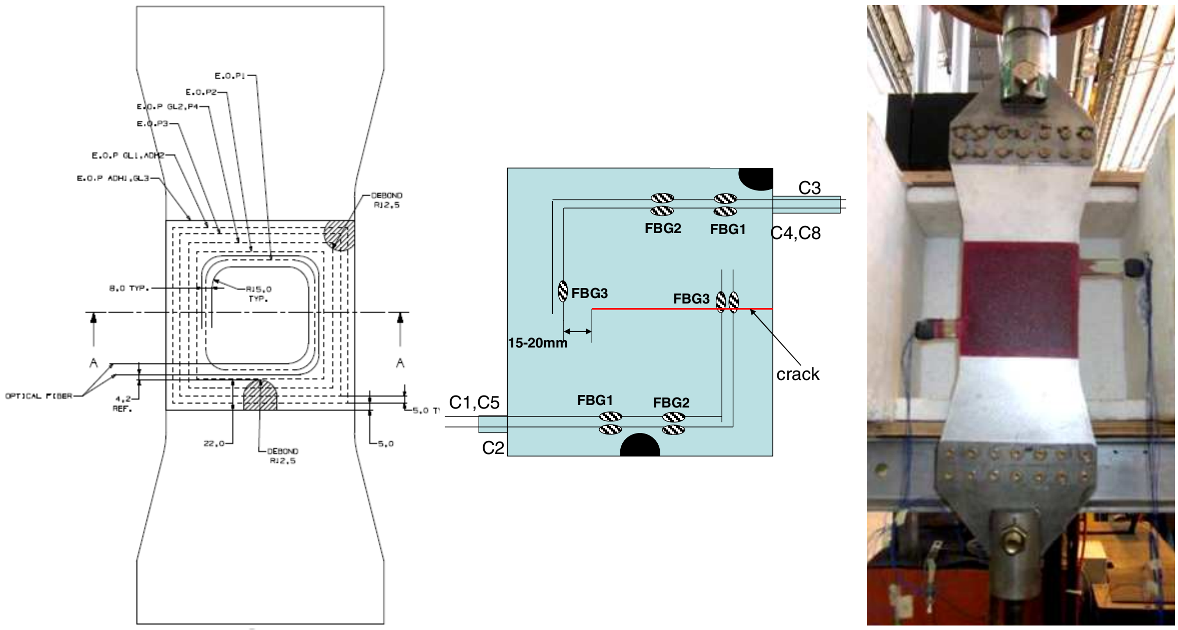

Figure 5: Left: Design of the Second Demonstrator. Middle: Bonding of the sensor mat and the repair patch on the second demonstrator. Right: second demonstrator in the fatigue test rig.

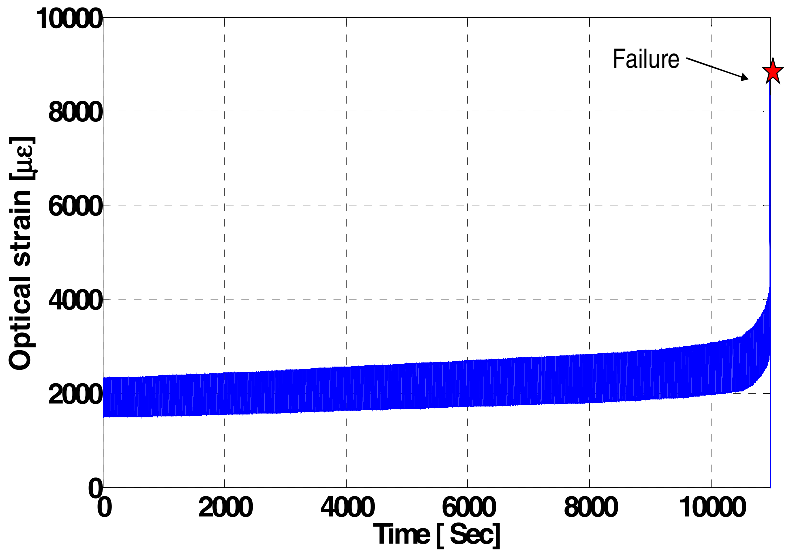

Figure 6: Typical FBG readings during final fatigue cycles of the demonstrator when the crack is approaching the sensor.

3 CONCLUSIONS

Monitoring of repair patches by an integrated sensing mat was shown to be a promising tool to detect repair patch debonding before it becomes a critical issue. The technique has been proven on simple sample specimen level made of typical aeronautic materials showing a very good agreement with FE models.

The performed tests of the structural demonstrators showed that the repair patch monitoring was working reliably, but in the tested cases no patch debond occurred so that the monitoring of a debonding patch could not be verified. More tests are necessary to demonstrate the performance of the repair patch monitoring also on this structural element level. The installation of the sensing mat was satisfactory and the egress of the optical fibers was sufficiently robust to survive the fatigue tests in the wide temperature range and the handling of the demonstrator.

The change in readings, of the low spatial resolution sensor net, in response to the growth of critical defects is significant enough to make a clear indication of patch deterioration with a reduced chance for misinterpretation. It is, therefore, hoped, that the use of such a system will allow a significant increase in the regular inspection intervals of bonded repairs without compromising safety.

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