Title: Smart Bonded Composite Repairs for Aging Aircraft

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ABSTRACT

A Fiber-Bragg-Grating based, advanced co-cured smart composite patch for the repair of metallic structures is proposed and demonstrated. A sensor net is tailored for real time strain monitoring at the patch critical locations. Tracing of strains development during patch curing and due to mechanical loading can be obtained, making this concept a candidate tool for airworthiness assessment of bonded repairs. Advantages include real time cure monitoring and long-term structural integrity evaluation during service.

INTRODUCTION

The concept of using bonded composite repairs for the maintenance of aging metallic aircraft has been proven both as a preventive measure and as a method for delaying future growth of existing damage [1]. The main advantages of a bonded patch repair as compared to a metallic bolted one are: smoother load transfer, elimination of additional stress concentration due to fasteners, good fatigue and damage-tolerance behavior of the composite patch and its easy application on curved areas.

The older composite repair concept uses a pre-cured patch, which is cured before being bonded to the structure, while in the more recent co-curing approach, the raw composite plies are laid, cured and bonded to the metallic structure in a single process. The co-cured concept eliminates the need for a lay-up and curing tools and provides better geometrical fit to the metallic substrate.

The curing process has a key influence on the long-term durability of the bonded repair. It is important to assure the right temperature over the entire patch area, otherwise, poor adhesion and patch mechanical properties may result.

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This is especially difficult to achieve under field conditions where most repairs are carried out. It is also important to monitor the repair integrity over time. At present, most commercial inspection procedures are based on detecting voids using ultrasonic techniques at scheduled maintenance intervals.

A bonded patch is usually designed such that its thickness is dropping off towards the patch edges. This is done to minimize the stress concentration at the adhesive layer near the edge, thereby preventing premature failure of the patch. This tapered area should be carefully monitored since debonds or delaminations at this area may grow rapidly, causing a catastrophic patch failure. The recently introduced smart repair concept [2,3] is aimed towards real-time assessment, based on direct monitoring of repair integrity using embedded sensors. In such approach repair failure may be predicted before any delamination or debonding may reach critical size.

Embedded Fiber Bragg Gratings (FBG), as well as extrinsic Fabry-Perot interferometric sensors have been used extensively to monitor strain and temperature in composite structures, during curing or service [4, 5, 6].

This work presents an advanced *co-cured* smart composite patch repair methodology using an embedded FBG sensor net, specially tailored to monitor repair integrity during service. The same embedded FBGs are also used for cure cycle evaluation. Cure cycle monitoring by FBG enables temperature measurements inside the patch at many locations and the estimation of the residual strains caused by the thermal expansion coefficient mismatch between the composite material and the metal substrate. The use of embedded FBGs may also replace the conventional electrical thermocouples that are now placed around the patch during curing. To the best of our knowledge, this is the first detailed description of a smart co-cured composite patch on a metallic substrate. By tailoring the FBG sensor locations to the specific patch design, we obtained strain reading at the patch most critical areas.

Experiment

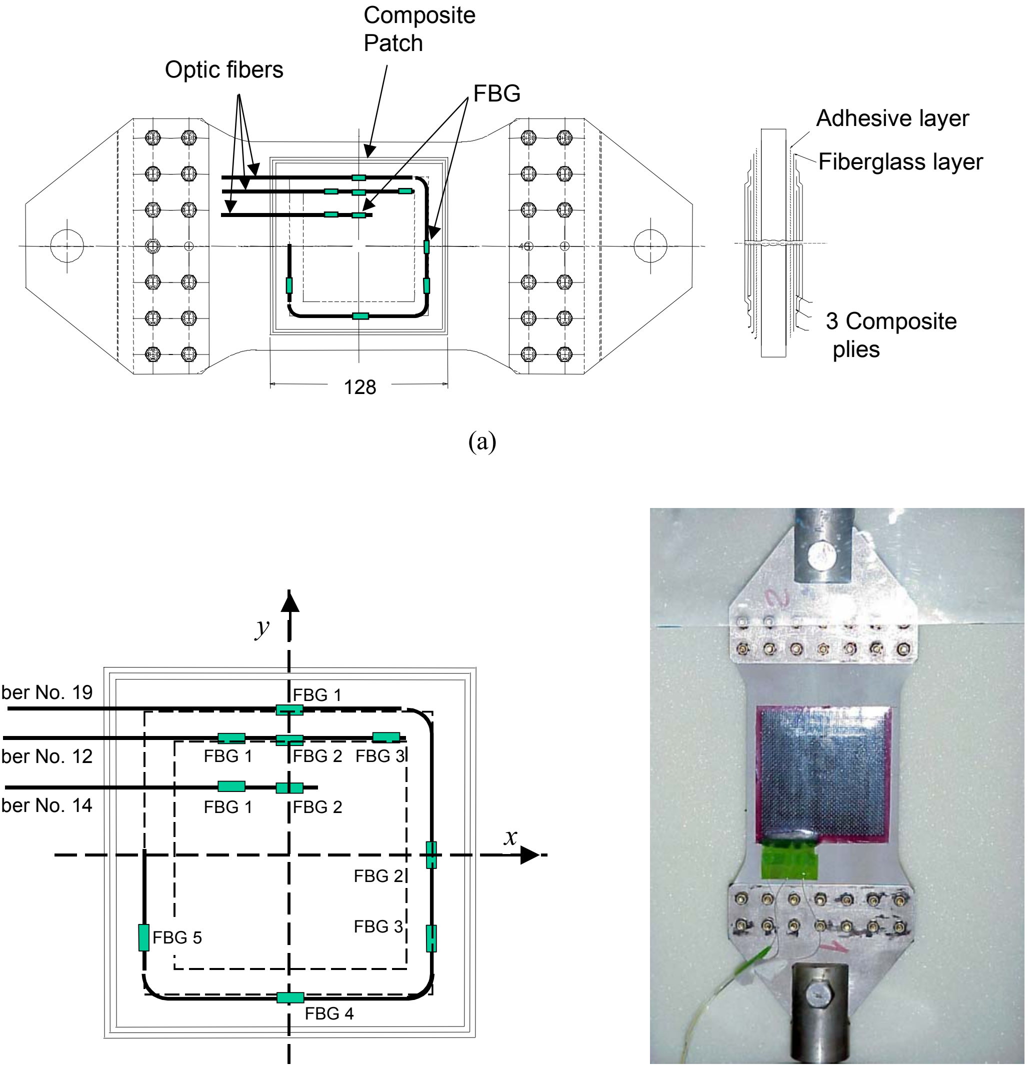
The specimen examined in this work represents a typical 100x100mm co-cured bonded patch repair (Figure 1). It comprises a carbon epoxy, double-sided patch, bonded to an aluminum plate (2024, 1.6mm thick). Each patch was made of three plies of Fiberite 753 style 3K-70-P carbon/epoxy plies and one ply of Fiberite 753 style, 120 fiberglass/epoxy prepreg. An adhesive ply was placed between each patch and the aluminum substrate.

Three polyamide-coated optical fibers were embedded into the upper patch, two in a direction parallel to the applied tensile loading and one, with 5 FBGs was embedded around the patch periphery. Fibers entered the patch through sealed PTFE tubes. An additional, free FBG sensor was placed near the patch for temperature measurement inside the vacuum bag during curing. All FBGs were written in our laboratory using the second harmonic of Argon-ion laser.

The patches, embedded with optical fibers, were co-cured and bonded to the aluminum plate inside a vacuum bag at 120°C for two hours. The average heating and cooling rates were 1°C/min. During the curing process, reflection spectra were measured using a fast wavelength meter, and the spectrum center of gravity was recorded as a function of time.

Typical raw $\Delta\lambda/\lambda$ data, representing the sensors reaction to both temperature and strain behavior, as a function of the temperature inside the bag are shown in Figure 2. A smaller reference patch, with only one FBG, was cured without being bonded to the aluminum substrate.

Tensile tests were performed in order to verify that the fibre readings, when embedded in a directions parallel and normal to the applied tensile loading, are in good correlation with analytic predictions. The specimen was tested by quasi-static loading to 27000N at a rate 0.1mm/min and FBG readings were simultaneously recorded in real time. An external FBG sensor monitored the ambient temperature during all mechanical testing.



(a)

(b)

(c)

Figure 1: Smart patch specimen: (a) Double sided bonded repair specimen design; (b) Embedded FBG net; (c) Smart patch specimen under tensile load.

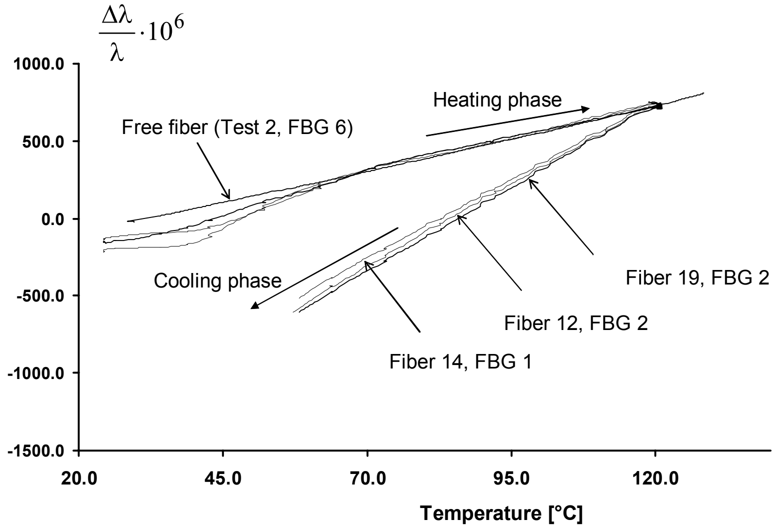


Figure 2: FBG readings during cure cycle of Co-cured composite patch over Al substrate.

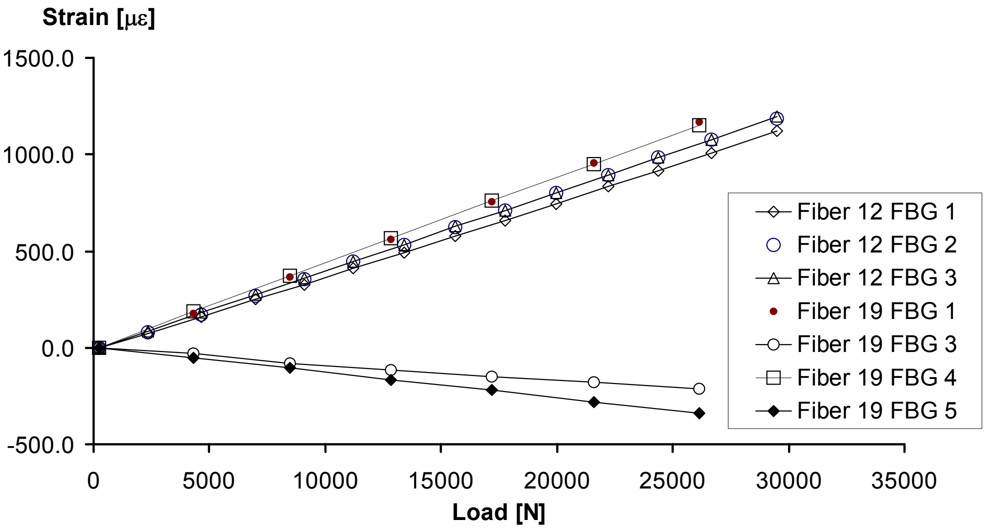


Figure 3: FBG readings during mechanical loading.

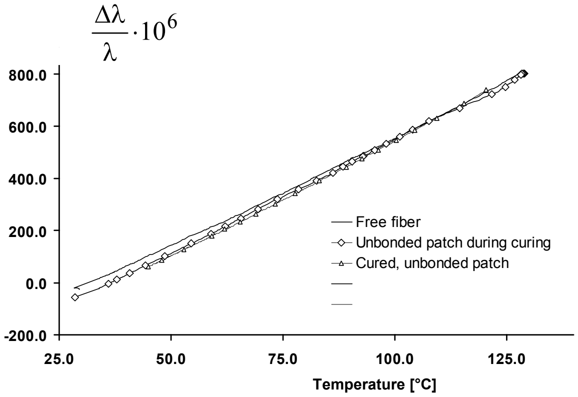


Figure 4: FBG readings of the unbonded patch during cooling phase.

DISCUSSION

During the heating phase, Figure 2, following initial brief "running in" stage (which is believed to be contributed to by the alignment of the optic fibres in the composite layers under vacuum pressure and which varied from fiber to fiber [5], the embedded FBGs' readings closely tracked those of the free FBG, indicating that the recorded wavelength shift was due to temperature rather than induced strain. Thus, this material system, under the above-mentioned curing process, has not developed mechanical load transfer capabilities before significant curing at 120°C. During the cooling phase, the free and embedded sensors responded quite differently: the free FBG simply behaved as a thermometer, retracing its heating route, whereas the embedded sensor was strongly affected by the compressive strain imposed on the patch by the contracting aluminum, whose thermal expansion coefficient is an order of magnitude higher than that of the composite matrix. The free patch, not bonded to the aluminum substrate, did not develop significant residual strains compared to a free FBG, during the entire cure cycle, Figure 4, indicating good matching between the thermal expansion coefficients of the optical fiber and the cured patch. Same behavior was also observed when a cured, unbonded patch was reheated and cooled down (the triangles in Figure 4).

Since the optical fiber and composite patch appear to have quite similar thermal expansion coefficients, $\Delta\lambda/\lambda$ data, representing the sensors reaction to both temperature and strain behavior, can be analyzed using the well-known formula:

$$\frac{\Delta\lambda_B}{\lambda_B} = (1-p_e)\varepsilon + (\alpha_\Lambda + \alpha_n)\Delta T\,, \qquad (1)$$

where ε is the mechanical strain, ΔT is temperature change, p_e is an effective strain-optic constant, α_Λ is a thermal expansion coefficient for fiber and α_n represents the thermo-optic coefficient [7]. Results for the mechanical strain, developed during the curing cooling phase, are shown in Figure 5.

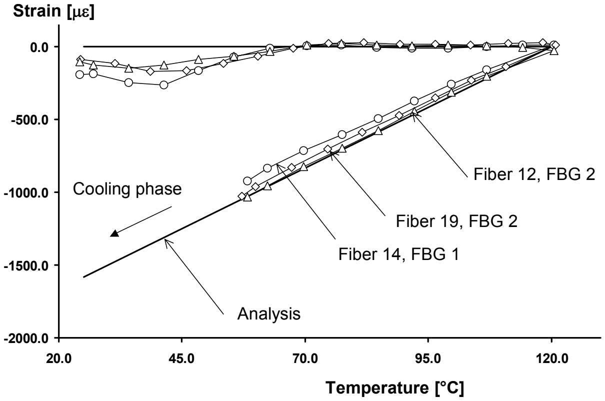


Figure 5: Mechanical strains developed during cure cycle.

Tensile tests were performed in order to verify that the fiber readings are in good correlation with analytic predictions. Finite Element analysis results for strain distribution along the vertical and horizontal axis (*x* and *y* axis, Figure 1b) are given in Figure 6.and Figure 7 Good correlation between analysis predictions and sensors readings was obtained. No separation of the reflection spectrum was observed during both the curing process and the mechanical testing [8].

Fatigue tests were also performed on a similar patch design in order to verify that the fiber itself, especially when embedded at the patch tapered zone, did not cause any delamination or debonding. No evidence of any defect was found after 50,000 cycles at constant amplitude of 220 MPa. Moreover, the FBG readings did not change over time, indicating that the sensor itself is not affected by cyclic loading and is firmly bonded to the composite structure. Specimens were also tested up to failure. Real-time strain measurements using the Bragg sensors clearly indicated specimen failure via metallic yielding rather than delamination or debonding.

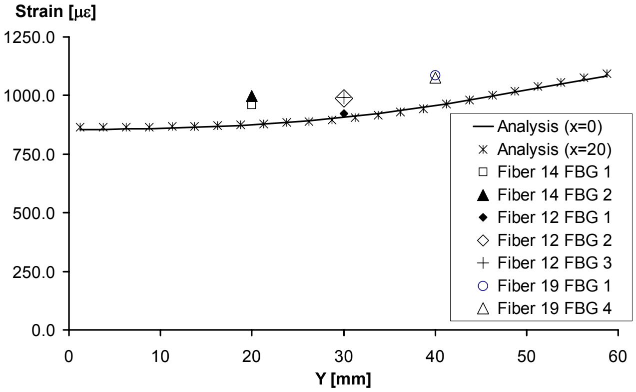


Figure 6: Mechanical loading test results:
x direction strain distribution at x=0.

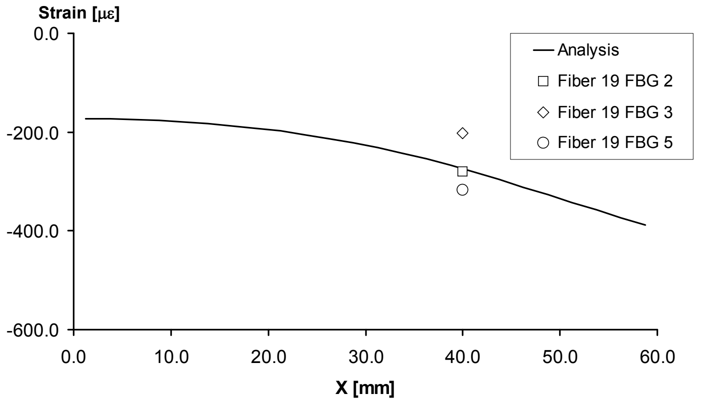


Figure 7: Mechanical loading test results:
y direction strain distribution at y=0.

CONCLUSIONS

In a co-cured smart patch, fiber Bragg gratings can be used to monitor and study the curing process. Since no residual strains developed during the heating phase of the curing cycle, fibre-based sensing can serve as a convenient tool for curing cycle heating rate optimization. Accurate readings of strain by the FBG placed parallel and perpendicular to the applied load substantiate the concept of multiplexing sensors on a single optical fiber that can be embedded around the patch periphery. The patch periphery is the location of stress and strain concentrations expected to cause patch or bonding failure, and it is in this area that structural integrity monitoring is required.

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