STIFFENER DEBONDING DETECTION MONITORING THE RESIDUAL STRAIN FIELD USING A DISTRIBUTED SENSING TECHNIQUE

A. Fernández-López[a*], A. Lozano-Martin[a], A. Güemes[a]

[a]*Laboratory of Smart Materials, Department of Aeronautics, Polytechnic University of Madrid,*
Plaza del Cardenal Cisneros, 3 P.C.28040 Madrid (Spain)
**antonio.fernandez.lopez@upm.es*

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Abstract

Fibre optic sensors are one of the best candidates to be embedded in advanced composite structures and potentially being used to monitor the structure during the operational live with Structural Health Monitoring (SHM) purpose. Stiffener debonding introduces changes in the close strain field that can be easily detected, but an extremely dense sensor network is required to carry out with aerospace requirements and determine the location and extension of the damage. Distributed sensing based on Rayleigh scattering allows performing debonding detection in a huge area by one single fully sensitive fiber. In this paper, the experimental measurements obtained are presented. Validation of the debonding detection capability of the proposed technique has been done using ultrasonic inspection.

1. Introduction

Detection of stiffener debonding is one of the key issues for Structural Health Monitoring (SHM) applications in the aerospace industry. Debondings due to impacts or hard landings during aircraft operation are actually one of the most common aircraft damages, and reduce significantly the strength, stiffness and fatigue life of the structure. In current composite structure design, safety is ensured by designing to requirements wherein damage is never allowed to grow and reduce the residual static strength of the structure below a specified value related with the maximum load expected in service. It could be useful to review those assumptions using advanced maintenance procedures, as SHM.

In an initial stage, stiffener debonding promotes local changes in the strain field, and the influence on the global stiffness is extremely low. For this reason, common detection SHM techniques are based on ultrasonic waves, such as Lamb waves or acoustic emission, to overcome the local effect of the damage and carry out an operative technique without introducing unrealistic high density sensor networks, that will be required for traditional techniques based on local strain measurements, as can be traditional strain sensors or Fiber Bragg Gratings. For this reason, this technique is unfeasible for real applications.

Distributed sensing techniques open the possibility of introducing a sensor network embedded in the structure with density enough to detect debondings in an early stage (previous to barely visible) introducing a low weigh penalty and a low cost, as the network consist of standard bare optical fiber. Previous distributed measuring techniques based on Raman and Brillouin effects offer the possibility to interrogate up to 10 Km of fiber, but with a special resolution over 10 cm and very poor sensitivity, that usually limit this techniques to civil structures [1].

By using the Rayleigh scattering distributed sensing technique; it is possible to obtain strain measurements all along the optical fiber, with a spatial resolution up to 5 mm and high strain accuracy (±1με) up to 2.000 meter long. These characteristics allow monitoring huge areas with a single fiber.

2. Experimental technique

Rayleigh backscatter in optical fiber is caused by random fluctuations in the refraction index profile along the fiber length promote during the manufacturing. The Rayleigh backscatter of a bare optical fiber looks like random fluctuations. These fluctuations are stable in absence of variations of external stimulus, as temperature or strain variations. Rayleigh backscatter amplitude can be modeled as a continuous weak Fiber Bragg Grating (FBG) with a random period. As usual with FBG sensing techniques, temperature or strain variations cause changes in the reflected spectrum, shifting the relative spectrum [2][3][4].

Rayleigh backscatter as function of length is obtained applying the Fourier transform to the complex reflection coefficient obtained by Swept Wavelength Interferometry. The scatter profiles from the two data sets are then compared along the entire fiber length along short length windows, which define the spacial resolution. Scatter signal is given by adding of two orthogonal polarization states, in order to obtain a polarization-independent signal. To quantify the local strain change, the backscatter complex signal along the fiber is transformed into the frequency domain.

The amount of change promoted by strain or a temperature variation in a segment of fiber is proportional to the spectral shift from this segment (see Figure 1-Left). Spectral shift is given by the complex cross-correlation function performed between two stages, a reference and a measured (see Figure 1-Right). Spectral difference between the shifted peaks of cross-correlation is directly proportional to the strain or temperature shift in a fiber interval, given by:

$$\frac{\Delta\lambda}{\lambda} = -\frac{\Delta\gamma}{\gamma} = K_{\varepsilon}\varepsilon + K_{T}\Delta T \tag{1}$$

Where λ is wavelength, γ is the frequency, K_{ε} is the strain coefficient and K_{T} is the temperature coefficient. Strain coefficient and temperature coefficient depends of the optical components of the stress-optic tensor. As can be easily deduced, strain and temperature resolution are linearly proportional to shift resolution. Shift resolution has a relation with special resolution because as longer the segment used better shift resolution. For this reason, size of the segment should be carefully selected to fix to the sensing situation [5].

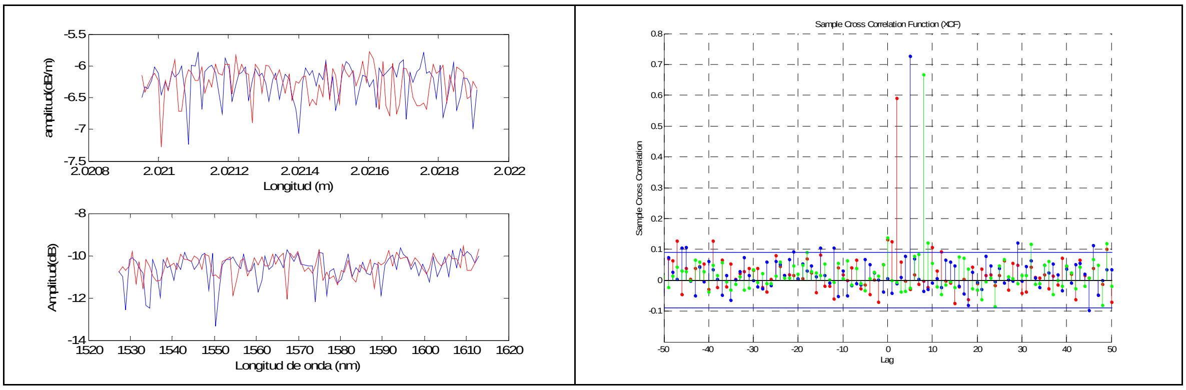

Figure 1: Rayleigh backscatter signal of a fiber segment and their spectrum (left) Cross-correlation of the reference spectrum with the measurements at three different strains levels (right)

3. Experimental test

3.1. Specimen description

The specimen subject of study is a composite skin (600x400 mm) co-bonded with a procured T stiffener 500 mm long. One optical fiber has been embeded during the curing process with a zig-zag configuration between the first two plies opposite to the stiffner side. The reason for reducing the spacing in the central area is to be able to monitor residual strain gradients in that area with an accurate special resolution, in order to determine an accurate damage area and damage location. Additionally, in order to trigger the onset of the debonding, a 20mm wide separator film (A4000) is introduced. The material used was prepreg UD carbon fiber with a thermoset matrix (Epoxy) AS4/8552 and the adhesive used for bonding is FM-73M.06, an Epoxy film with carrier, manufactured by Cytec

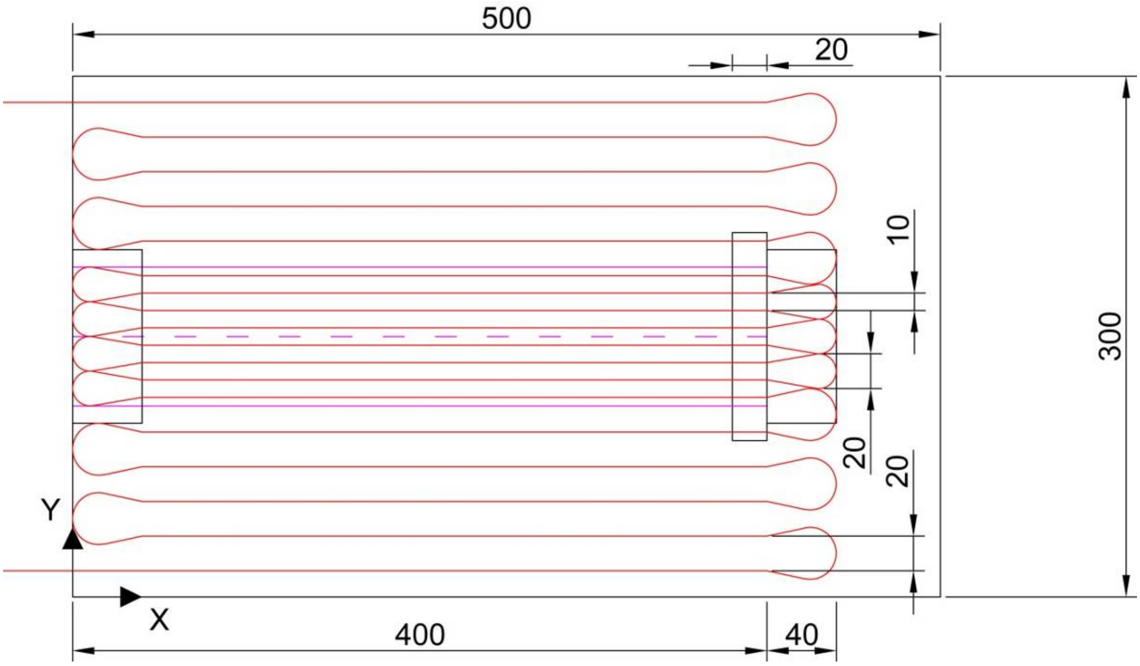

Figure 2: Scheme of the fiber optic sensing network dispose embedded in the structure

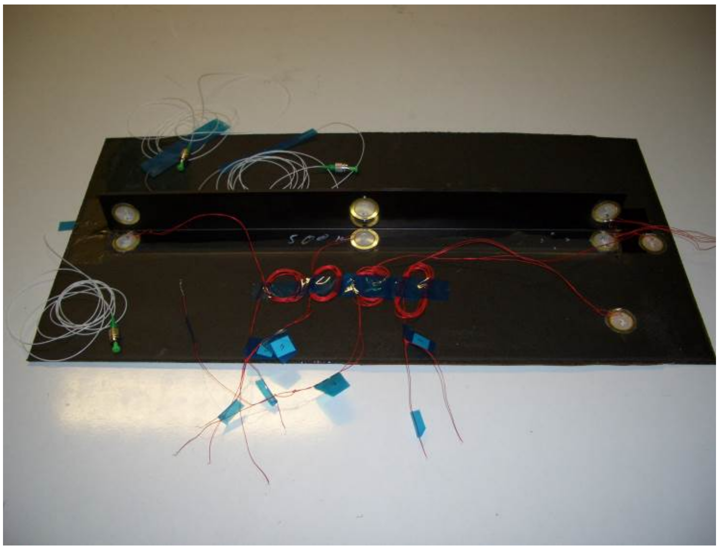

Figure 3: Picture of the test sample plate

3.2. Test Set-up and test description

Stiffener debonding is promoted by a fixed tool to the stringer. Peeling stresses are applied using a screw, in order to promote a progressive debonding. A picture of the used tool can be seen in Figure 4.

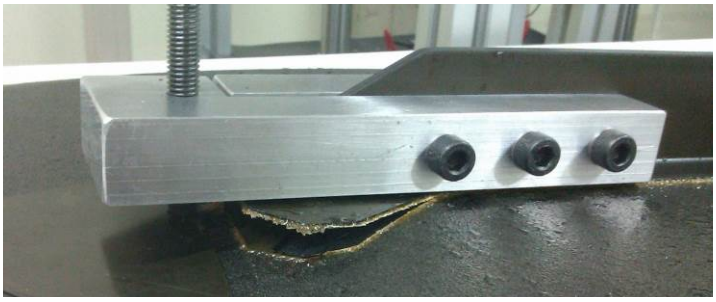

Figure 4: Picture of stringer debonding process

Stiffener debonding is promoted in progressive steps, and strain is measured all along the embedded fiber using an OBR 4600 with the loaded structure. Afterwards, load is removed and strain is again measured using the same procedures. This couple measures are performed in every load step. The objective of measuring strains with the load structure is to identify the strain changes promote close to the damage area. However, damage not only can be determined due to these changes, as the stiffener debonding promotes a relaxation of residual stresses close to the damage. This effect can be observed in the strain measured with the unload structure.

3.3. Test results

In figures 5 and 6 it is presented the strain distribution of all along every sensor line. Debonding peeling stresses are appliead on the left and increases with the load applied. As close the sensor line is to the stiffener location (the center of the plate), as high are the strains over the plate. Furthermore, damage can be tracked studying the strain peak position.

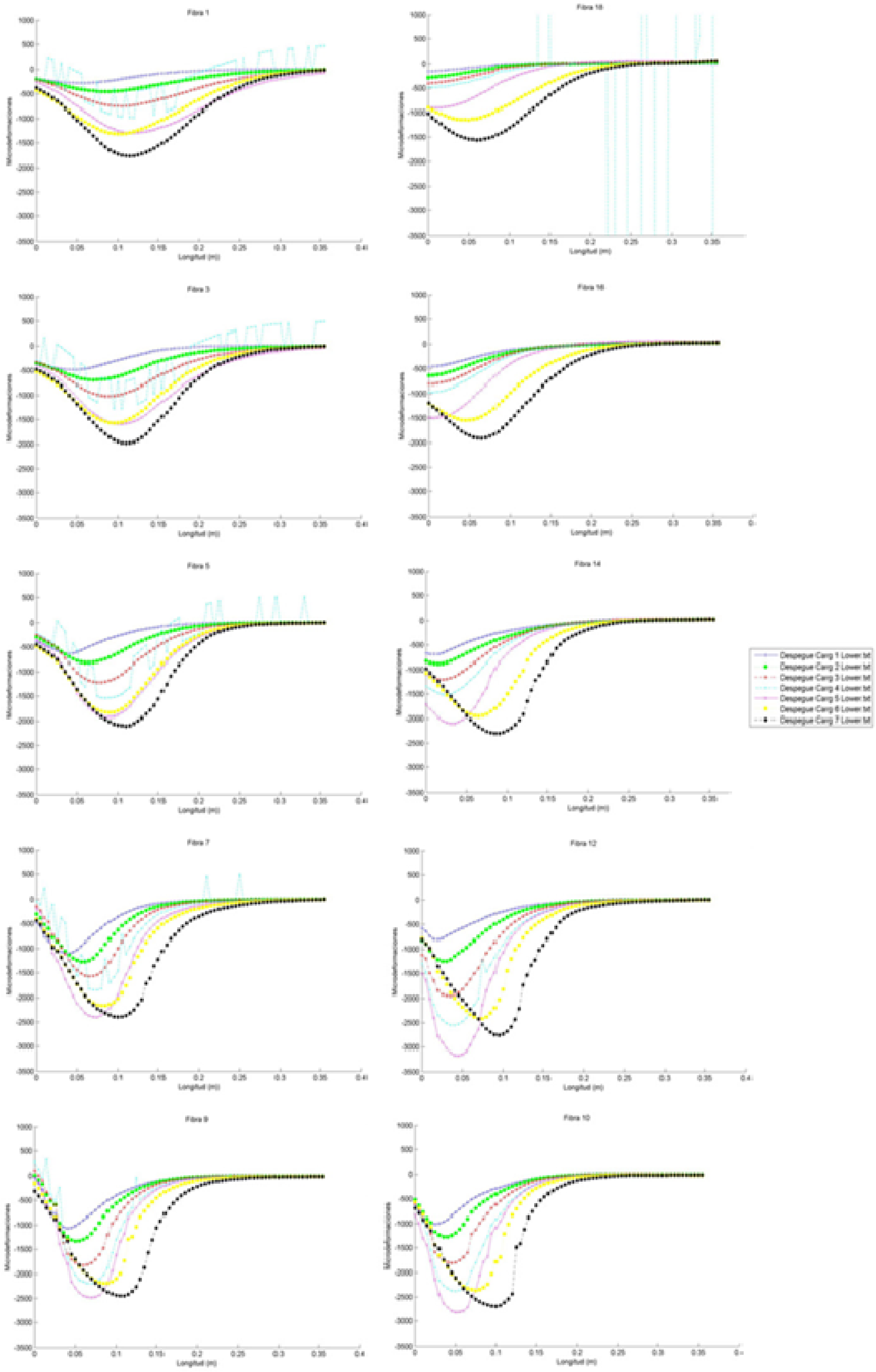

Figure 5: Strain measurements of every sensor line from the lateral side of the plate (top) till the center (botton) with the load structure

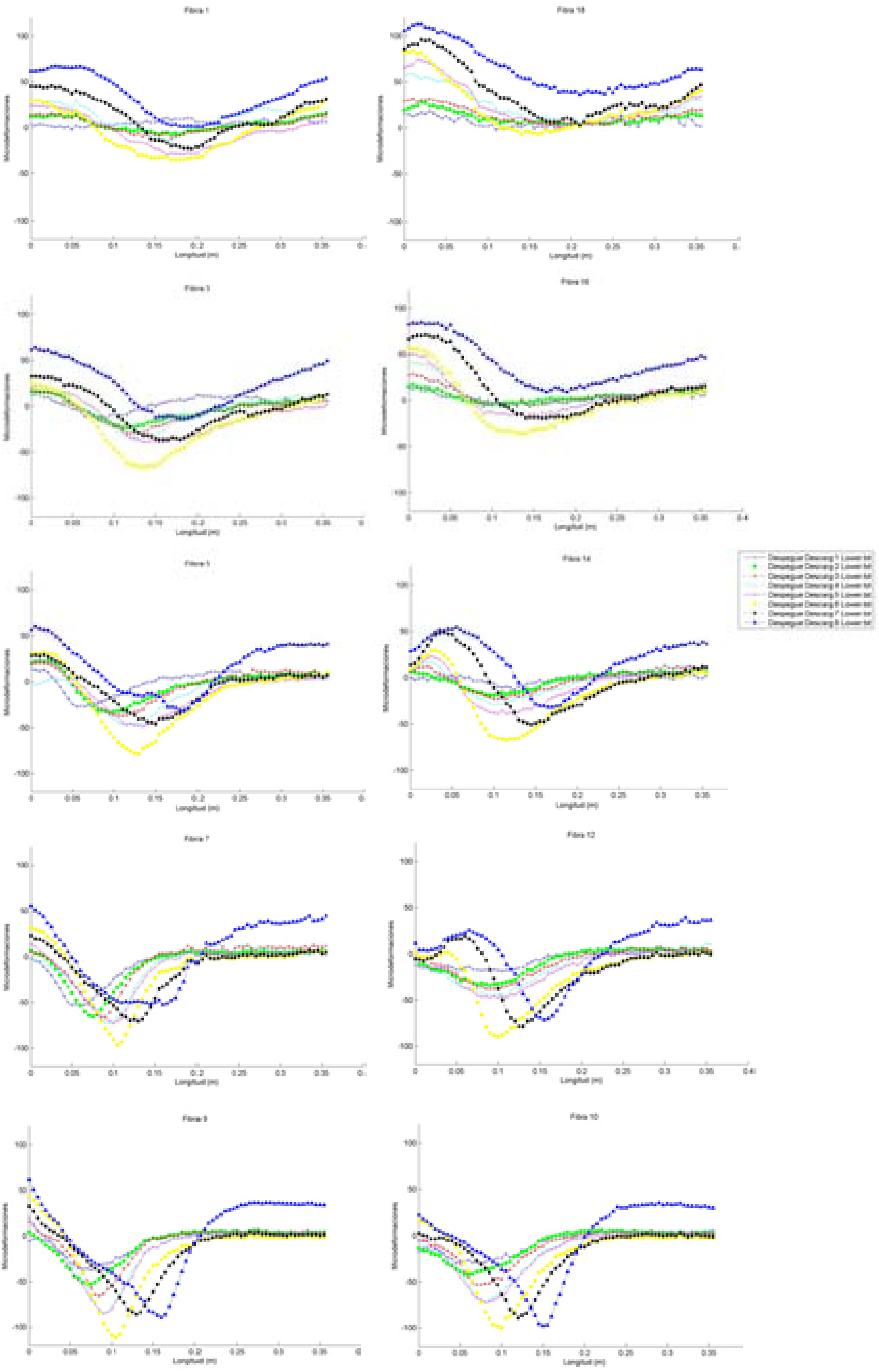

Figure 6: Strain measurements of every sensor line from the lateral side of the plate (top) till the center (botton) with the unload structure

Strain measurements can be easily presented as strain maps using the sensor special distribution to present the strain information of all fiber. Once the strain information is presented in this way, strain concentration due to damage appearance is easily to be determined in a load structure. However this strain concentration can be easily relate with damage appearance, it is not easy to determine the real damage area. For unload structure is also a strain concentration around damage due to the relaxation of the residual stresses, but opposite to the load structure, as this strain distribution is only promote by damage, residual stress area has a direct relation with the debonding area.

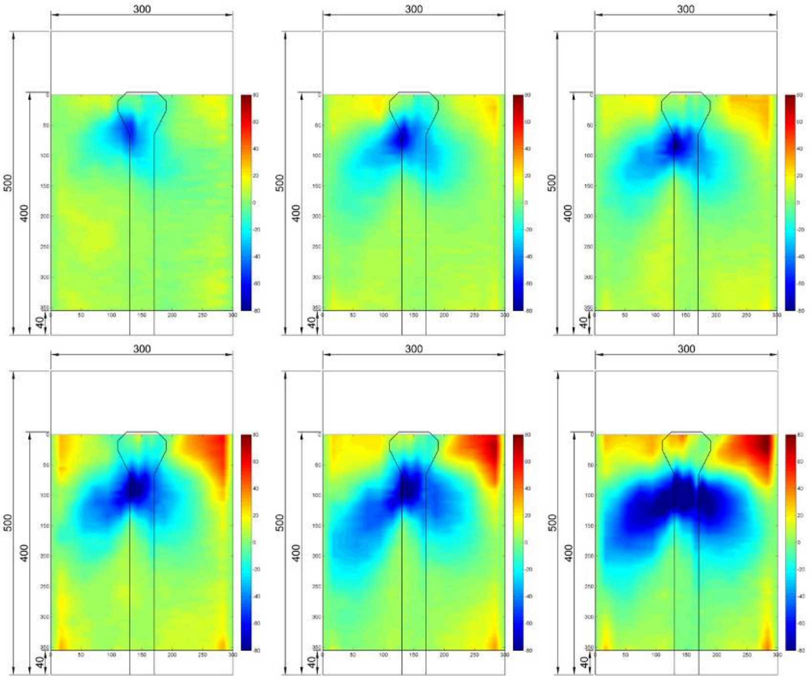

Figure 7: Strain maps of the load structure after different load stages

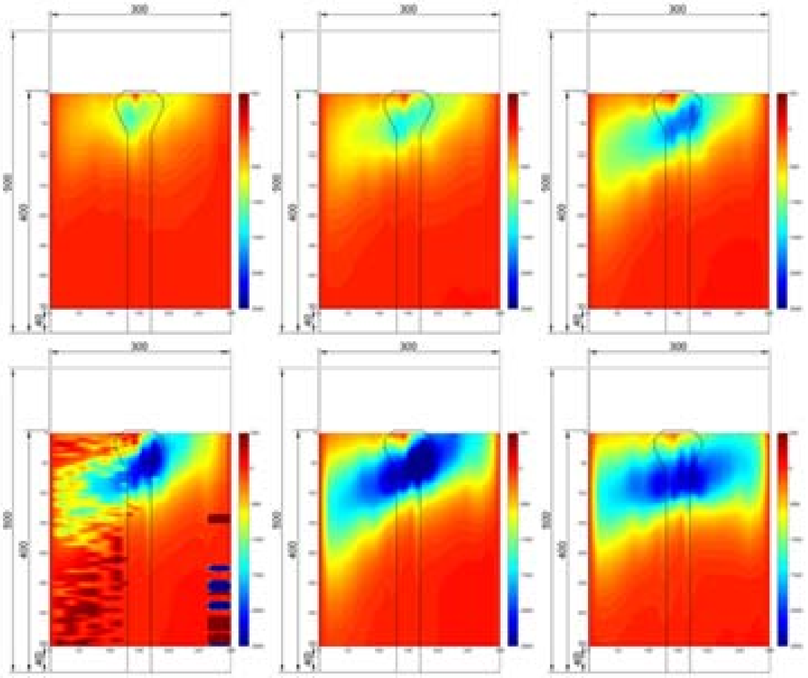

Figure 8: Strain maps of the unload structure after different load stages

4. NDI Comparison

In order to verify the real extension of the damage a C-Scan inspections of the structure was carried out. The result of the last damage stage is presented and shows a good similarity to the residual strain map obtained with the distributed sensing technique. Figure 9 displays last damage stage which is recorded quite accurately by the sensor network.

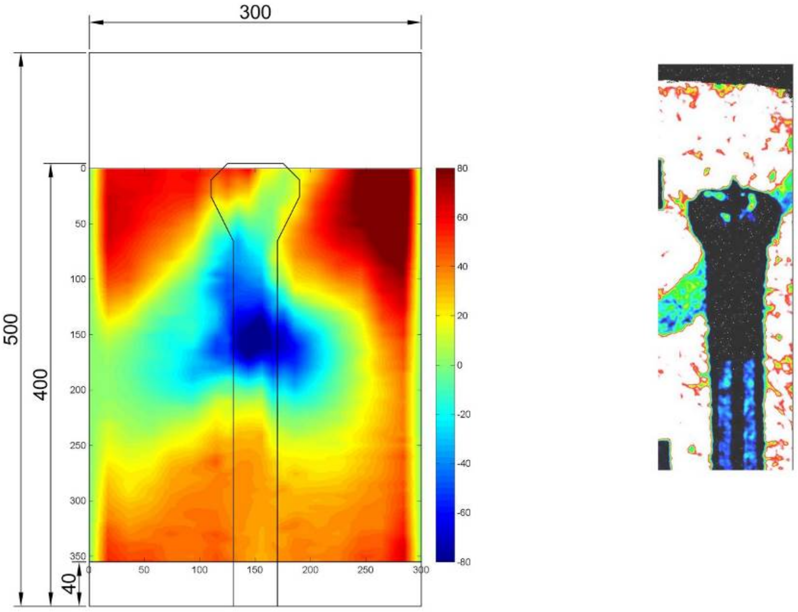

Figure 9: Strain maps of the unload structure and C-SCAN of the stiffener area

5. Conclusions

Distributed sensing open the possibility of detecting small damages in composite materials, such as stiffener debonding, by using the data given by the strain field. High density strain sensor networks can be obtained introducing small additional weight. Changes in the strain field induced by the stiffener debonding were easily measured with this technique. This technique cannot only by applied to load structures; unload structures residual stresses can provide useful information to determine damage location and damage area with high accuracy.

References

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