DAMAGE DETECTION IN A STIFFENED CURVED PLATE BY MEASURING DIFFERENTIAL STRAINS

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Abstract

The most typical aeronautics structure is a skin (plain or curved) reinforced with stringers and ribs. The main problem for this kind of structures is to verify the conditions of the bond line and to guarantee this joint during maintenance and certification tasks.

A reliable method to monitor debonding failures during the operational life of the airplane is proposed in this paper. The principle for this technique is to detect the differences of strains between two closely located sensors in loaded structure. Damage changes the stiffness and, for different applied loads, changes the strain field distribution in the structure. Unless the sensor is very close to the damage, the changes in strain readings use to be very small. The differential strain approach allows detecting damage at further distances. Fiber Bragg Grating sensors are used as high accuracy strain sensors.

Experimental tests were done on a representative specimen. Analytical approach was also made by Finite Element Model (FEM). The possibilities of damage detection algorithm for real time debonding monitoring are discussed.

1. Introduction

Actually, most of aeronautic structures use a semimonocoque design with a thin skin and stiffener elements such stringers and ribs. Advance composite materials allow a high optimization for this kind of structures due to the directional properties and the possibility to integrate different subparts by co-curing or co-bonding process in a monolithic design. Airbus A380 section 19, the rear section of the fuselage, is a representative example for this kind of structures (Fig. 1).

Fig. 1. Airbus A380 Section 19

The main problem for this kind of structures is to verify the condition of the bond line in the interface of the different subparts. Adhesive mechanical properties may change with time, temperature and humidity, variable conditions during the operational life of the aircraft. Also, small impacts in the surface can promote delaminations in the bond line, which also induced the debonding of the stiffener from the skin. Sometimes, rivets are added to ensure the structural integrity.

Nowadays, the methodology used for aircraft maintenance is based on schedule-driven inspections, and the quality of the joint is ensured with non-destructive techniques (ultrasounds, tomography, etc). Structural Health Monitoring (SHM) concepts will increase the safety and the weight savings by providing a less time consuming maintenance methodology, determining the presence of damage at an early stage, allowing easier local repair in an integrated design or to replace the damage component in a modular design.

Two different SHM approaches are feasible, passive and active approach. In a passive SHM system only sensors are needed and “natural” sources like impact, stress, vibrations or acoustic emission are detected. An active SHM system requires also actuators, that provide an optimize response for damage detection with the introduction of weight penalty by the equipments.

In this paper we propose a SHM passive technique to detect stiffener debonding at an early stage during the aircraft operation by using paired Fiber Bragg Grating (FBG) sensors.

It has been obtained experimentally, and it is justified also by numerical methods, that the stiffener debonding may cause small changes in the strain distribution, even when the sensors are located more than 300 mm. away from the crack. These changes will usually go undetected unless we compare the readings of two closely located sensors (differential approach). The concept work very efficiently and repetitively for different crack lengths and loading conditions.

2. Damage detection method based in the stiffness correlation

The principle for this technique is to detect the stiffener debonding from the skin analyzing the strain field for different load levels. Debonding change the strain field over the full structure in case any subpart (stiffener element or skin) has a continuous load applied, due to the change of the load transfer throw the bonding line.

Detect changes in the structure with a strain sensor require an accurate model of the structure and a precise knowledge of the forces applied to the structure. These requirements are difficult to carry out in a real airplane, but this technique is already used for simulated damage in small components.

Very close to the joint, strains are similar because of the strain compatibility at the interface of the subparts, but debonding cause a redistribution of loads that change slightly the strains field.

As damage changes the strain field, damage can be detected measuring the difference of strains between two closely located sensors when the structure is loaded. Sensors should be located in each subpart of the joint.

3. Fiber Bragg Grating Sensors

FBG is a periodic modulation of the refractive index of the core of an optical fiber. The index modulation is induced by exposing the fiber to an ultraviolet beam. The FBG acts as a narrow band reflection filter. The reflection wavelength is depending upon the pitch of the grating, which is sensitive to the strain and temperature (Eq. 1).

$$\frac{\Delta\lambda}{\lambda} = (1-\rho_{\alpha})\Delta\varepsilon + (1+\xi)\Delta T \qquad (1)$$

Where λ is the Bragg wavelength, ρ_α is the photoelastic coefficient of the fiber, and ξ is the thermo optical coefficient. FBGs sensibility measurement is sensitive to temperature and strain.

4. Test Specimen

As a representative section of a real fuselage, the specimen chosen was a curve composite panel 1340 mm length 400 mm wide built in carbon/epoxy tape AS4/8552 with $[+45,-45,0,90]_S$ lay-up and cured in autoclave with a omega stiffener.

Four optical fibers have been bonded in its surface with six FBG each. One optical fiber has been bonded over the skin and other one over one side of the stringer, one pair for every side of the stringer. FBG distribution along the fiber was the same for all of them, and fibers are bonded to locate the sensors by pairs (Fig. 2)

Every pair of close fibers has the same sensor distribution and wavelength, to reduce wavelength strain and temperature perturbations. Difference of strain of two close sensors is given by equation 2

$$\varepsilon_1 - \varepsilon_2 \approx \left(\frac{\Delta\lambda_1}{\lambda_1} - \frac{\Delta\lambda_2}{\lambda_2} \right) \frac{1}{1-\rho_\alpha} \qquad (2)$$

Where λ_1 is the wavelength of the sensor bonded over the stringer and λ_2 is the wavelength of the sensor bonded over the skin.

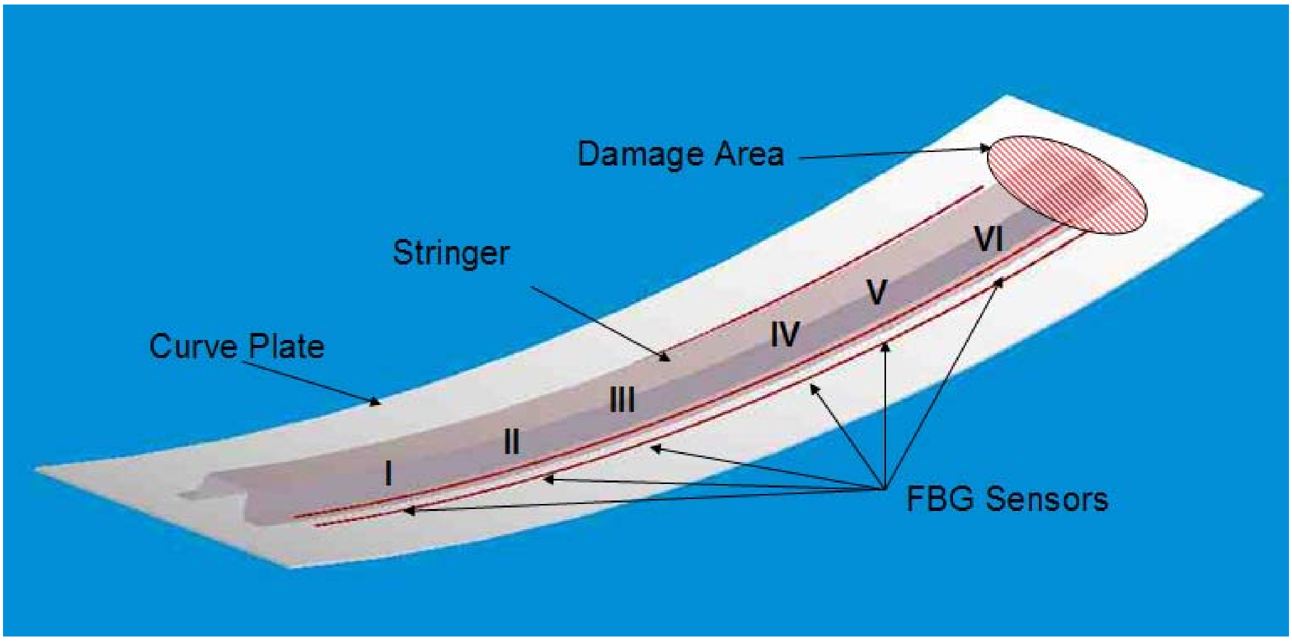


Fig. 2. Test specimen: Composite curve plate with a stringer

5. Experimental Results

The specimen is tested under a load stage introduced with a compression bar in the stringer, promoting the debonding of the stringer from the skin by a flexion load.

Fig. 3 shows the different strain field in the fiber direction for the same applied load. It shows many differences in the strain field distribution along the full structure, but only presents a small gradient between the stringer and the skin.

The difference of strains between two near sensors depends on the applied load. We plotted the difference of strains of a pair of close sensors versus the strain of one of them located over the flange of stringer, which is used as reference.

Before any damage develops, the difference of strains between the sensor over the stringer and over the skin must be lineal for every pair of sensors. This was verified experimentally and with FEM.

When the stringer debonds the near stress field changes significantly, even most of the structure preserves the mechanical properties. Damage promotes a strain redistribution of the non-near field, depending of the load state of structure.

Analytical results from sensors I, II and III (figs. 4, 6 and 8), located 875 mm, 675 mm and 575 mm. from the damage, respectively, present a slight difference between the strains of the stringer and the skin. Damage introduces a change of linearity which increases with the proximity to the damage.

Experimental data could not be able to detect any difference between damage and undamage structure for these sensors.

Sensors IV and V (375 mm and 275 from the damage, respectively) showed changes on the stiffness. Damage promotes a strain redistribution of the non-near field, depending of the load state of structure. In figures 11 and 13, purple represent data before introducing damage, and pink and yellow after damage was caused. For certain levels of load, the behavior is clearly different from the initial stage (pink), making possible to discern the presence of damage. Under a low level of load, damage and undamage structure has a similar strain field (yellow) and damage detection can not be performed. Analytical results for sensors IV confirm this behavior (Fig. 10)

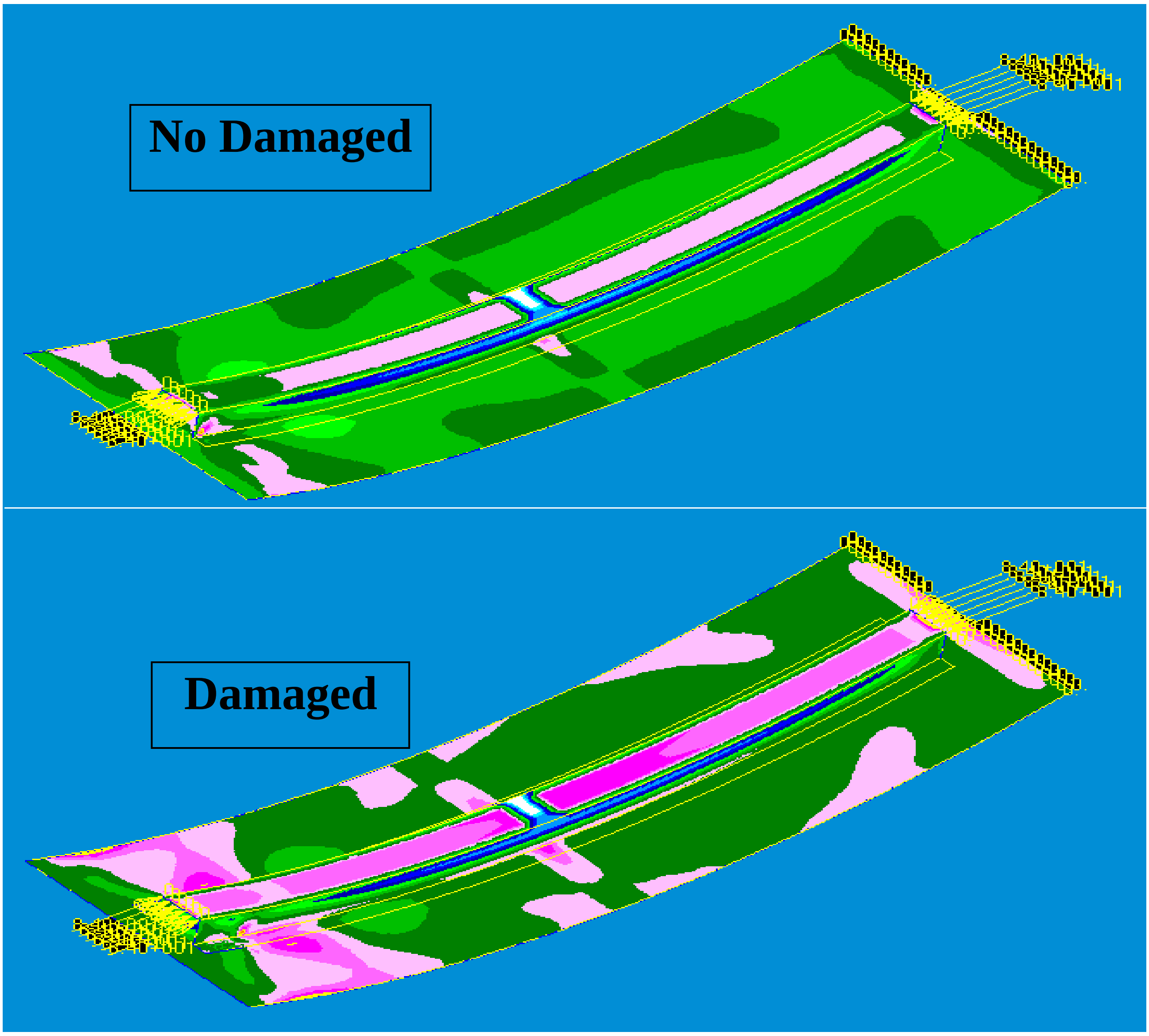


Fig. 3. Strain field in the fiber direction for undamaged structure (up) and damage structure (down)

Sensors VI (75 mm from the damage) show non-lineal changes due to the proximity to the damage. FEM results present a different residual strain due to the proximity of the debonding area. Difference between experimental results and FEM can be explained with discrepancies on damage geometry. Damage's geometry and the distance between damage and sensors were estimated by a visual inspection.

Pairs of Fiber Optic Sensor, on the left and on the right of the stringer, present similar results due to the symmetrical damage geometry and forces.

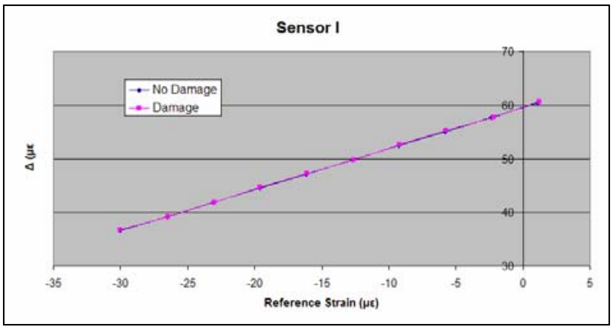


Fig. 4. Sensors I analytical values for the difference of strain versus the strain over the stringer. (875 mm from the damage)

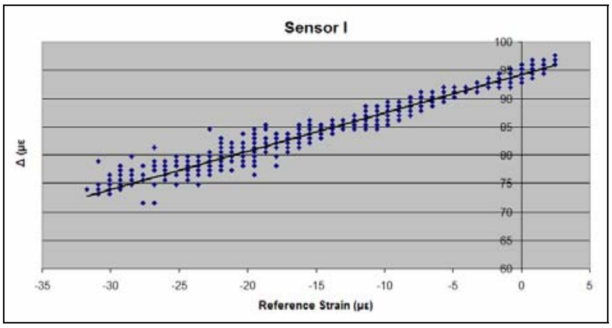


Fig. 5. Sensor I Experimental values for the difference of strain versus the strain over the stringer. (875 mm from the damage)

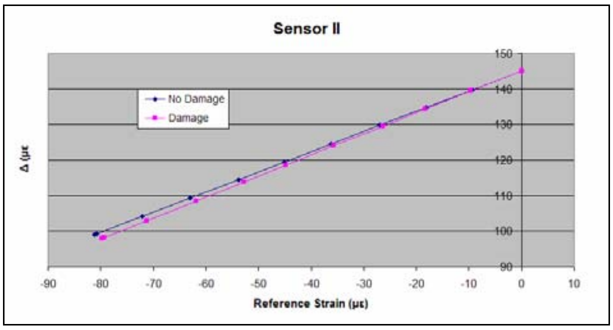


Fig. 6. Sensors II analytical values for the difference of strain versus the strain over the stringer. (675 mm from the damage)

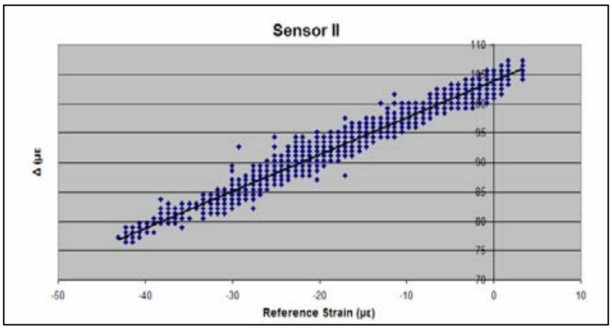


Fig. 7. Sensor II Experimental values for the difference of strain versus the strain over the stringer. (675 mm from the damage)

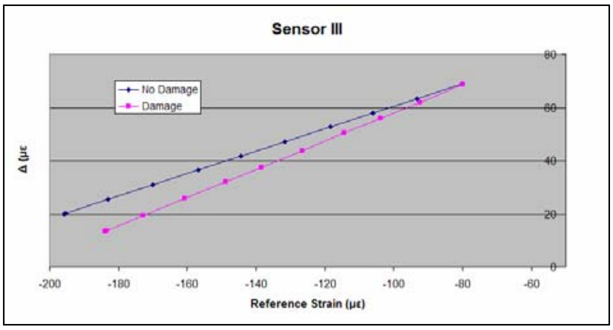


Fig. 8.Sensors III analytical values for the difference of strain versus the strain over the stringer. (575 mm from the damage)

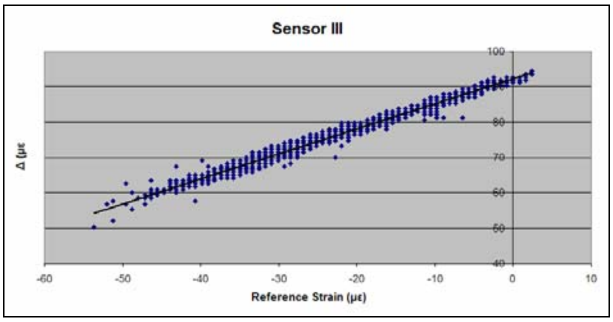


Fig. 9. Sensor III Experimental values for the difference of strain versus the strain over the stringer. (575 mm from the damage)

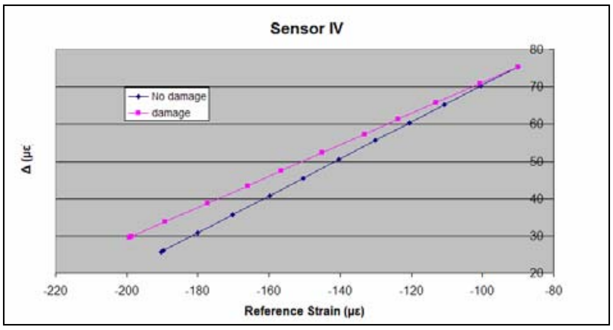


Fig.10.Sensors IV analytical values for the difference of strain versus the strain over the stringer. (375 mm from the damage)

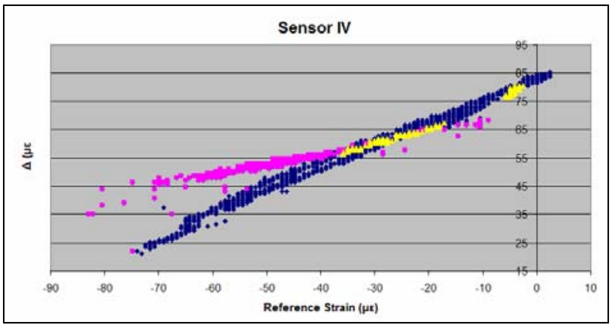


Fig. 11. Sensor IV Experimental values for the difference of strain versus the strain over the stringer. (375 mm from the damage)

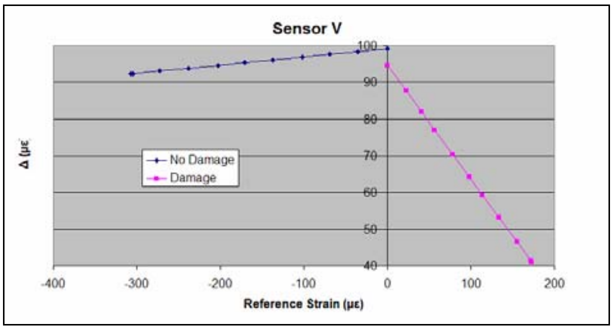


Fig.12.Sensors V analytical values for the difference of strain versus the strain over the stringer. (275 mm from the damage)

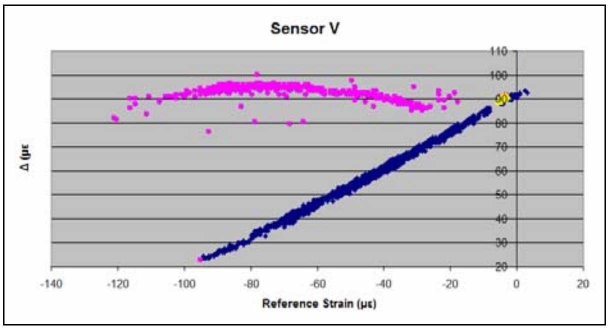


Fig. 13. Sensor V Experimental values for the difference of strain versus the strain over the stringer. (275 mm from the damage)

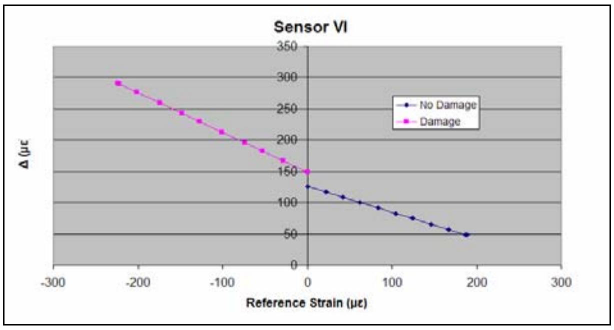


Fig.14.Sensors VI analytical values for the difference of strain versus the strain over the stringer. (75 mm from the damage)

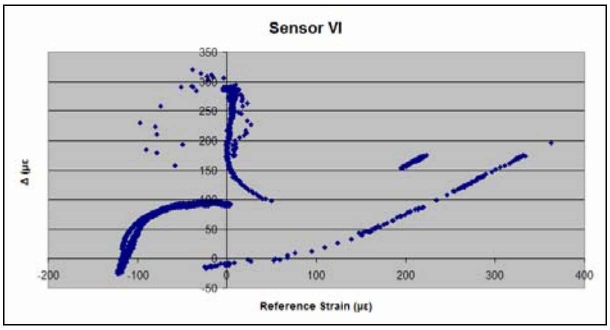


Fig. 14. Sensor VI Experimental values for the difference of strain versus the strain over the stringer. (75 mm from the damage)

6. Damage detection algorithm

The debonding of reinforcement element can be monitored based in the previous principle.

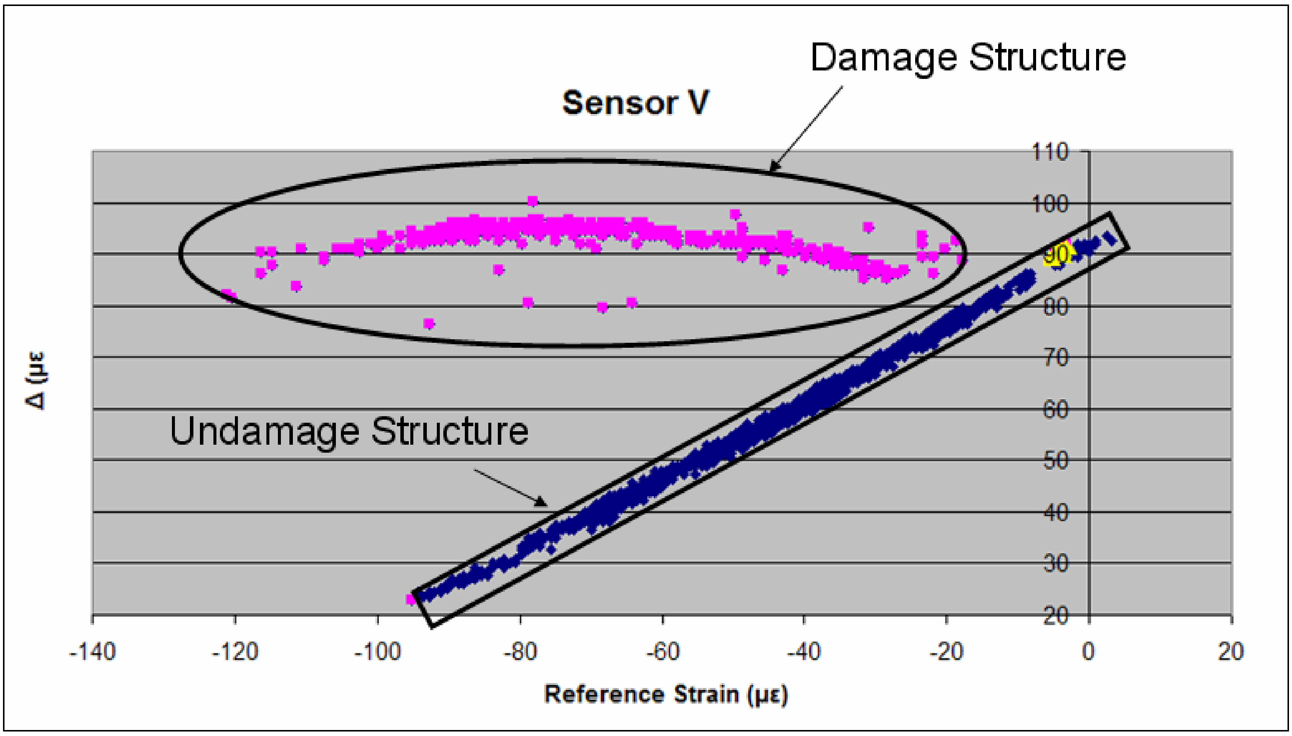
6.1 Learning phase (undamaged structure)

To determine the response of the pristine structure it is necessary to submit the specimen until the expected load envelope of the structure. Without damage, the ratio between the strains is lineal with the variation of wavelength of one of the sensors.

For every pair of sensors, the damage envelope chosen in this case is the rectangle cantered on the minimum square line, and the area of this envelope includes the 99% of the data acquired during the learning phase.

6.2 Detection Phase

Debonding changes the stiffness and change the ratio between the pairs of sensors. This way, damage is detected by a pair of sensors when more than certain number of consecutive points is out of its damage envelope. This number is chosen in order to avoid false alerts.



7. Conclusions

Structures with stiffeners or bonded stringers can be monitored monitor by measuring changes in the near stress field. Damage detection depends on the distance between damage and sensor and on the load applied to the structure.

Conventional approach of detecting changes in the strain field requires a precise knowledge of the applied load, and the sensor need to be quite close to the damage.

A new approach has been presented to increase the sensitivity of the technique, so each pair of sensors covers an extensive area. Detection performance is limited to certain load range, depending of the damage geometry.

Fiber optics sensors are the most suitable to detect this kind of failure. This technique is easy to automatize. A damage detection algorithm is proposed.

8. References

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