8th European Workshop On Structural Health Monitoring (EWSHM 2016), 5-8 July 2016, Spain, Bilbao
www.ndt.net/app.EWSHM2016

FREE-EDGE DELAMINATION LOCATION AND GROWTH MONITORING WITH AN EMBEDDED DISTRIBUTED FIBER OPTIC NETWORK

Patricia F. DÍAZ-MAROTO [1]*, Antonio FERNÁNDEZ [1], Beatriz LARRAÑAGA [1], Alfredo GUEMES [1]

[1] Laboratory of Composite Materials and Smart Structures, Dpt. Aeronautics,
UPM, Plaza Cardenal Cisneros, 3 - Madrid 28040 SPAIN. p.fernandezdm@aero.upm.es

Key words: Fiber Optic, Distributed sensing, Aerospace SHM applications, Delamination, Rayleigh scatter, OBR.

Abstract

Delamination is the most characteristic damage found in composite materials. Low velocity impacts may lead to delamination onset, likely to occur during manufacturing processes or in operating service life. Furthermore, areas near the free-edge of the structures, as well as ply drop off and integrated reinforcements have demonstrate a high vulnerability to impacts.

This paper focuses on the delamination detection based on an embedded or fixed fiber optic network in a composite laminate. The sensor network uses the Rayleigh scattering through an Optical Backscatter Reflectometer (OBR) that it obtains a continuous strain monitoring on a bare opical fiber. For this purpose, several optical fibers were attached on the structure surface close to the free edge of the specimens in order to identify the first-ply failure and the delamination growth. Experimental results were compared to an ultrasonic C-Scan inspection which present a good agreement with the data of sensor network.

1 INTRODUCTION

Nowadays, composite materials are widely used in aircraft structures due to their high specific properties, which become a high strength and stiffness relative to weight. It takes these advantages into account regarding the interests of aerospace field since it means a significant weight and fuel saving. However, the major disadvantage of composites is related to their sensitive under impact that it can induce a critical internal damage, which may not easily visible and detectable on the impacted surface. Several low velocity impacts may occur during assembly processes and also in operating service life by accident [1-3]. Parts of the structure more likely to undergo impact damage are located near its free-edge. Moreover, the loading condition effects on free-edge in composite laminates have been widely investigated by different authors including experimental tests and FEM simulations [4, 5]. These researches attempt to describe edge-delamination onset which is dominated by interlaminar shear stress, though it may be triggered by the interlaminar normal stress. Furthermore, stress loads can be concentrated easier near free-edge of composite laminates where impacts are expected to occur. Therefore, stresses prompt a debonding between adjacent plies and also identify the starting point to the delamination onset when stacking sequence changes its orientation.

The aim of this paper focuses on the early detection of accidental impact damage by means of a distributed fiber optic network. This technology provides strain and temperature measurement from numerous sensors placed all along the optical fiber with very high spatial resolution. Several SHM researches have been performed with this technique in this laboratory proving its high performances [6-9]. For that reason, distributed sensing is one the most suitable technique for detecting local cracks that will act as a ply-failure initiation point. Furthermore, the main advantage of this technology over conventional Non Destructive Inspection methods lies not only in the large surfaces that can cover by bonding only one optical fiber, but also on the inspection time requires for this operation.

For this purpose, different composite laminates were manufactured by hand lay-up and then impacted with a drop-weight testing machine. The main goal is to detect local changes from the strain field and also to study the influence of two types of low velocity impacts. Finally this research pursues to be representative for detection of free-edge delamination in aircraft composite structures such as man-holes, which are vulnerable to endure this damage. Durability of these structures will be improved with the application of this technique of strain monitoring as well as the inspection costs.

2 MEASUREMENT PRINCIPLE - OBR

Rayleigh scattering is caused by random fluctuations in the refractive index when an optical fiber is manufactured. The fiber optic network used in this paper to measure Rayleigh scattering is carried out by the Optical Backscatter Reflectometer (OBR). The OBR is an Optical Frequency Domain Reflectometer (OFDR) that uses a swept-wavelength interferometry by means of a tunable laser to interrogate the device under test (DUT) with high spatial resolution. Functioning schema of an OBR is shown in Figure 1.

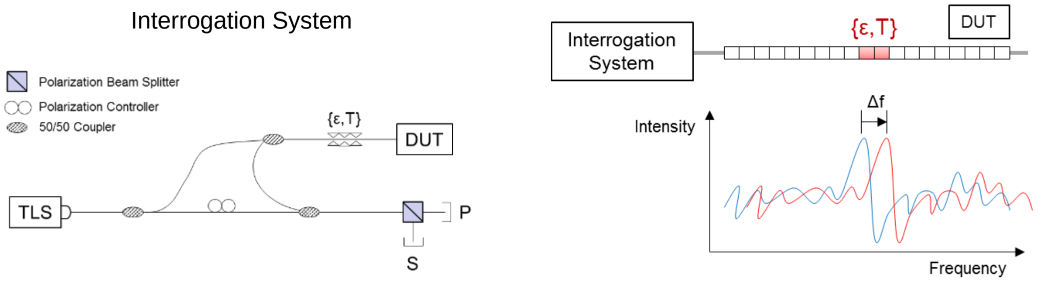
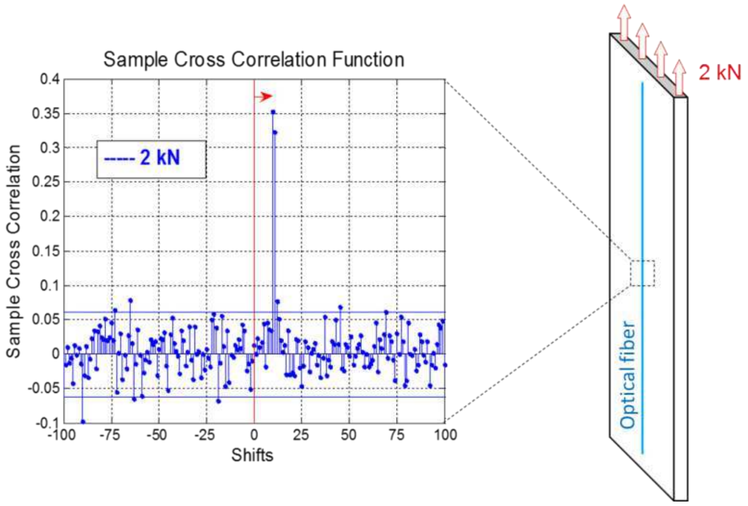


Figure 1: Schema of function of Optical Backscatter Reflectometer

Total reflectivity is calculated by the vector sum of two orthogonal polarization states (‘s’ and ‘p’). Once the complex reflection coefficient is obtained in the frequency domain, the reflectivity as a function of the fiber length is obtained via a Fast Fourier Transform [10]. Then, the reflected spectrum experiences a shift when a segment of DUT is strained or heated. In order to determine this spectral shift, a cross-correlation has to be performed between the two fiber states, the reference and the loaded. The spectral shift is linearly dependant on temperature and strain changes at each segment as shown in Equation 1.



$$\frac{\Delta\lambda}{\lambda_0} = -\frac{\Delta\nu}{\nu_0} = \mathrm{K_T}\Delta\mathrm{T} + \mathrm{K}_{\varepsilon}\Delta\varepsilon$$

Equation 1

Figure 2: An aluminium sample under tensile test. A cross-correlation function is performed between the reference and the strained measurement (under 2 kN load) in order to calculate the amount of spectral shifts. Through the Equation 1 strain and temperature changes can be obtained for one sensor which belongs to optical fiber bonded on plate surface.

When the overall shifts are calculated by a cross-correlation for each segment along the DUT, a distributed measurement is achieved. Sometimes, signal reflectivity becomes attenuated as a consequence of fiber optic loops and transverse stresses. In that case, the calculation of spectral shift turns out cumbersome.

3 DELAMINATION DETECTION FROM RESIDUAL STRAIN MEASUREMENTS

Distributed fiber sensors act as a strain sensor that can provide a full coverage at the region of interest by bonding one optical fiber. When a delamination occurs inside the laminate the fiber bonded on the surface undergoes compression and tension stresses. These stresses become residual strains which are used as an indicative of delamination onset. For that reason, after each impact a measurement of the strain field is recorded in order to detect small strain changes between the last structure states. Figure 3 shows the residual strains of each fiber sensors after different impacts.

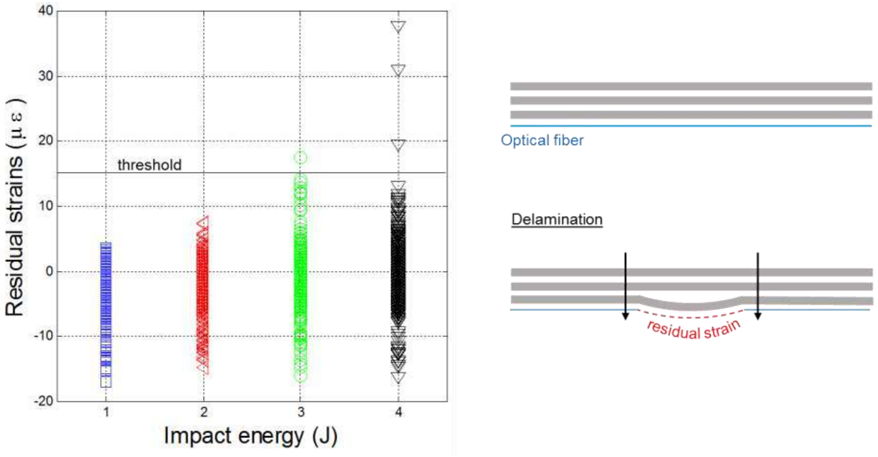


Figure 3: Measurement of residual strains after impact. (Right) Optical fiber behaviour when delamination turns up.

4 EXPERIMENTAL SEP-UP

Delamination is likely to occur at ply-interface when it has different fiber orientation. In order to cause an early delamination two stacking sequences were prepared with a cross-ply lay-up $[0_n/90_n]_S$, where n is the number of repeated layers. Composite laminate plates were made with a 200 mm long and 80 mm wide which were manufactured with carbon/epoxy prepreg AS4/8554 by Hexcel®. The ply thickness is 0.15 mm with a total of 16 plies for each symmetric laminate n=2, 4.

The distributed fiber optic network only was placed near the free-edge of the specimen where delamination is expected to appear. For this purpose, it is necessary to build a high-density network in order to detect all changes in the strain field. Furthermore, two types of optical fiber were used during the experimental impact test. First, acrylate coating when fiber was bonded on surface plate. Polyimide coating was employed when fiber is embedded into the laminate. Polyimide optical fiber is recommended to use for this experiment due to its small diameter and high temperature resistance, necessary when laminate has being curing. One optical fiber were divided in 6 paths and aligned parallel to the free-edge of the specimen covering the whole surface area as shown in Figure 4.

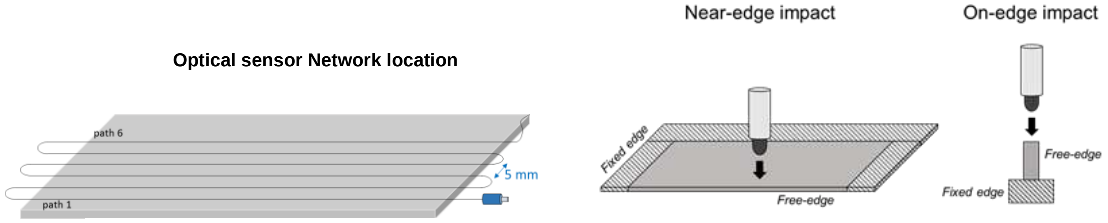


Figure 4: (Left) Fiber Optic network bonded to the surface arranged in 6 paths with a separation of 5 mm among each other. (Right) Types of impact

A drop-weight testing machine has been used to impact the five specimens under different energy levels until the onset of delamination. The impactor mass was constant (5 kg) and was adjusted at different heights in order to obtain the energy for delamination.
As expected, impacts carried out near-edge incurred in out-of-plane shear between adjacent plies which promotes a delamination that may not visible on the laminate surface, meanwhile impacts on-edge caused axial tension which may lead to edge cracking. As shown in Table 1 impact specifications are explained.

Specimen no.	**Stacking sequence**	**Impact energy [J]**	**Impact conditions**	**Fiber optic Network specifications**
1	$[0_4/90_4]$	[2, 6, 10]	Near-edge	Fixed on surface
2	$[0_4/90_4]$	[1, 2, 3, 4, 5]	On-edge	Fixed on surface
3	$[0_2/90_2]$	[1, 2, 5]	On-edge	Fixed on surface
4	$[0_2/90_2]$	[2, 4, 6, 8]	Near-edge	Fixed on surface
5	$[0_4/90_4]$	[2, 3, 5.8, 6,8]	Near-edge	Embedded first-ply

Table 1: Specifications of experimental set-up

Boundary conditions and constraints of the specimens used during test depend on the type of impact. On-edge specimens were positioned with clamps which leave a free-edge on surface top. Meanwhile, for the near edge impact metal plates were used along the perimeter of the specimen leaving a free-edge close to the impact zone. Figure 5 shows the set-up in detail.

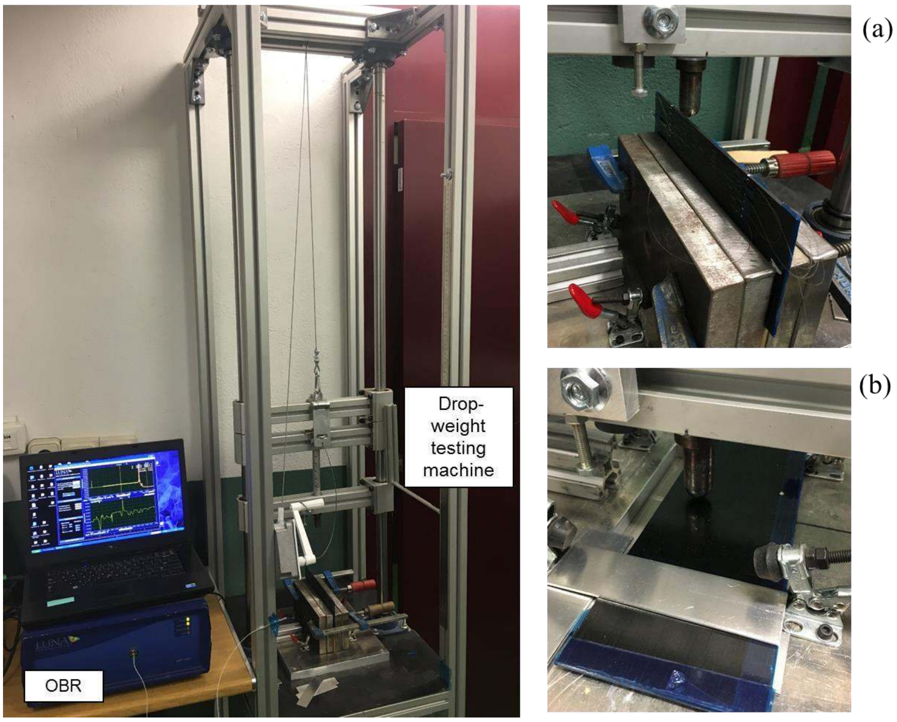


Figure 5: Set-up for impact test. (a) On-edge impact. (b) Near-edge impact.

5 EXPERIMENTAL RESULTS

After impacts were performed it could be appreciated that the strain field experienced small changes promoted by a delamination, understood as an internal damage. Delaminated area causes debonding in different plies that becomes in permanent residual strains close to the optical fiber. Assuming a perfect strain transfer from the matrix to the optical fiber, distributed sensors can record these strain changes related to delamination onset.

Optical sensor results have been obtained successfully and proved to be a suitable technique to detect these residual strains from internal damage. In order to validate this methodology fiber optic results have been compared to a Non-destructive Inspection by ultrasonic C-Scan techniques which have shown a good agreement.

5.1 On-edge impact

As expected, on-edge impacts have been more clearly detected, since this delamination cause an edge cracking and a permanent indentation. In order to predict the failure of the first ply, fiber optic paths were placed in both sides of the free edge. Results of the specimen 2 as shown in Figure 6 have a stacking sequence $[0_4/90_4]_S$ thus there are two interfaces susceptible to initiate the delamination. Face A has a strain level higher than face B, which it is an evidence of delamination appeared at the interface close to this face. When delamination is reached a high local strain peak is evident in the path close to the damage location. Despite the strains level is quite small, sensors can easily detect these changes in the strain field.

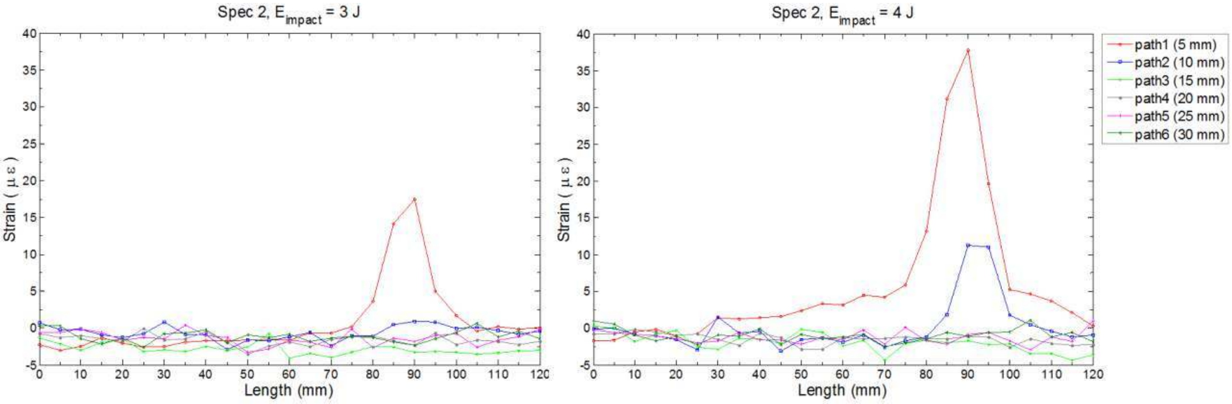


Figure 6: Strain field for different fiber optic paths. Distance from free-edge are shown in brackets.

A post-processing signal has been performed in order to obtain an improved visualization of strain data on surface laminate. Strain map is representative of the state of the structure. The growth of the delamination is much more appreciated in face A since the ply debonding was placed in that side. For this specimen, since fiber optic were fixed in both faces, ultrasonic technique cannot be applied.

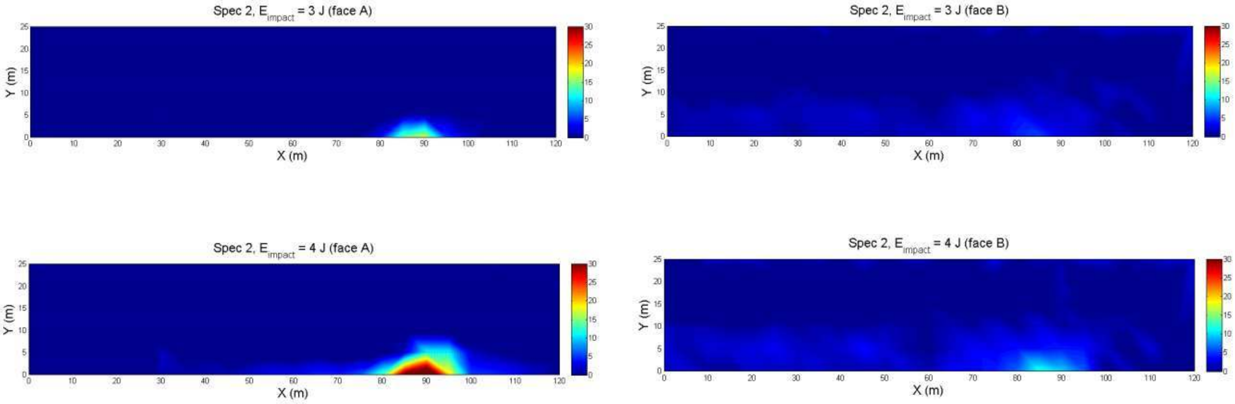


Figure 7: Color Map Strain field for on edge-impact. Both faces are represented to determine the onset of first-ply delamination.

It should be pointed out that after the 4 Joules impact permanent damage was caused in the free-edge and it was strong enough to penetrate the free-edge. Also, optical fiber was broken at the point of the impact. In spite of this damage produced a change quite small in the strain field it could be detectable by a single optical fiber.

Figure 8: Specimen 2, before (left) and after (right) impact test. Delamination is closer to face A of the laminate.

5.1 Near-edge impact

Near-edge impact promotes damage with a different profile than on-edge impacts. In these tests, the plies debonding by delamination effects were obtained inside the composite laminate and not to show up a barely visible impact damage as seen in on-edge impact.

The most typical shape when laminate has a stacking sequence with cross-ply is the "peanut shape". This type of delamination was observed after this impact test. It should be emphasized that for this specimen the optical fiber was embedded in a crooked configuration in the opposite side of the impact. For this case an ultrasonic inspection could be carried out. Figure 9 shows a C-Scan inspection and it can be observed a damage placed between 50 and 70 mm along the free-edge of the structure. As expected, delamination appeared in the opposite interface of impact face.

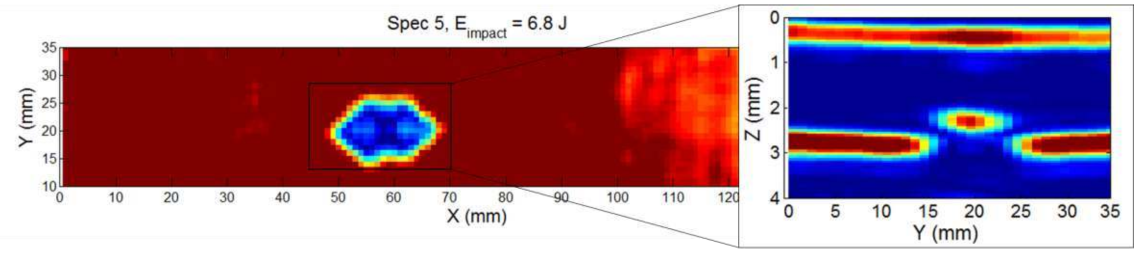


Figure 9: Ultrasonic C-Scan inspection. Delamination region is zoomed to visualize the ply failure

Distributed strain measurements collected by the OBR were taken after impacts. Each measurement has been compared to the last one in order to obtain the residual strains for each impact step. The crack growth of the delamination can be monitored with a strain mapping performed at every step. After 5.8 Joules impact it should be pointed out how delamination grew close to the first local strained area. Last impact recorded the strain field changes around 200 $\mu\varepsilon$ at the same position of ultrasonic results which demonstrated the reliability of the results.

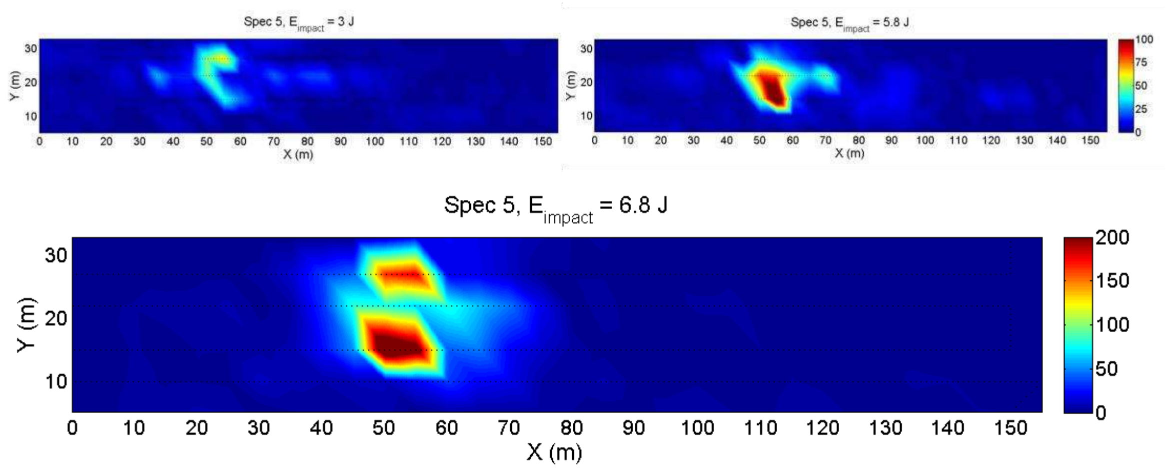


Figure 10: Upper Left: Strain map after impact of 3 J. Upper right: Strain map after impact of 5.8 J. Lower: Strain map after impact of 6.8 J.

6 CONCLUSIONS

Distributed fiber optic sensing has demonstrated to be a suitable technology to monitor the state of the free-edge in composite laminates after accidental impacts. For this purpose, residual strains have been used as a damage index that may predict delamination onset. They have been successfully measured with the dense optical network of distributed sensors placed on surface edge. Delamination damages appeared in all tests after different energy levels and they were detected with high accuracy and strain resolution.

For on-edge impact cases, permanent indentation was clearly detected that produced a visible damage on-edge. However, fiber optic network gave an additional information about the interface debonded which it could not detectable by a visual inspection. For near-edge impact cases, delamination cannot be detectable by a visual surface inspection. However, distributed measurement also provided a valuable information about the residual strain field which allowed to predict the location of internal damage after each impact.

The whole strain data obtained from distributed sensors could be very useful to improve the maintenance of the structures under free-edge impacts since this optical network allows for covering great areas with a single line of fiber optic. The enormous amount of sensors can be used to perform a strain mapping in order to improve the damage location. Furthermore, the use of residual strains field has demonstrated to be a proper index of delamination presence. All of these features take an important advantage in comparison with ultrasonic inspection method which is highly sensitive to small flaws in the material, the scanning time is quite significant and also the inspection requires a free surface.

The overall results highlight the potential of distributed sensing technique to monitor the edge of composite structures which are vulnerable to undergo impact damage and opens new possibilities for structural health monitoring.

REFERENCES

[1] Malhotra A. & Guild F. J., Impact Damage to Composite Laminates: Effect of Impact Location. Appl Compos Mater (2014) 21:165–177

[2] Hocheng H., Tsao C.C., Comprehensive analysis of delamination in drilling of composite materials with various drill bits. Journal of Materials Processing Technology 140 (2003) 335–339

[3] Long S., Yao X., Zhang X., Delamination prediction in composite laminates under low-velocity impact. Composite Structures 132 (2015) 290–298

[4] Malhotra A., Guild F. J., Pavier M. J., Edge impact to composite laminates: experiments and simulations. J Mater Sci (2008) 43:6661–6667

[5] Guillamet G., Turon A., Costa J., Linde P., A quick procedure to predict free-edge delamination in thin-ply laminates under tension. Engng Fract Mech (2016)

[6] Güemes A, Fernández-López A, Fernández Díaz-Maroto P, (2014) Damage detection in composite structures from fibre optic distributed strain measurements. In Proceedings of the 7th European Workshop on Structural Health Monitoring 2014, Nantes, Francia.

[7] Güemes, JA, Fernandez-Lopez, A, Soller B. 2010 "Optical Fiber Distributed Sensing. Physical Principles and Applications" J. Structural Health Monitoring, Vol. 9, No. 3, 233-245.

[8] Criado, A., Riezu, M., Fernandez, A. and Oizm, A. 2009. "Evaluation of OBR for strain measurements in blade testing". Proceedings of European Wind Energy Conference, Marseille, France.

[9] Güemes, J A, Menendez, J M, Frovel, M, Fernandez, I, Pintado, J M. 2001 "Experimental analysis of buckling in aircraft skin panels by fibre optic sensors" Smart Materials and Structures Vol. 10, no. 3, pp. 490-496.

[10] Soller, B. J., Wolfe, M., and Froggatt, M. E. 2005 "Polarization resolved measurement of Rayleigh backscatter in fiber-optic components." Optical Fiber Communication Conference and Exposition and the National Fiber Optic Engineers Conference Technical Digest. Anaheim, California.