Damage Detection by Load Path Changes in Reinforced Composite Panels Using Local FBGS and Distributed Sensing

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ABSTRACT

A SHM technique based on the load path changes has been used to identify debondings in two blades stiffened space grade composite panels. These panels have been instrumented with Fiber Bragg Gratings Sensors, FBGS. The egress of the optical fiber from these panels was made in one panel with pig tails and in the other with embedded optical connectors. Additionally to the local FBGSs, distributed sensors based on the Rayleigh backscattering effect have been embedded in the skin of the second panel. This sensor technique assesses the strains along the entire optical fiber length not only in the stiffeners but also in the skin of the panel. Both techniques have been compared during compression tests of the panels and their ability to detect damage has been evaluated.

Very good agreement has been obtained between strain measures of local and distributed sensing. The distributed sensing technique enables to asses the load path changes very detailed in a global strain mapping of the entire structure, identifying stiffener breakage, skin/stiffener debonding and buckling effects. The distributed sensing has demonstrated its high potential for damage detection of stiffened panels made by fiber placement technology using the load path change assessment.

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INTRODUCTION

A possibility to detect damages in structural elements is by assessing the change of the load paths within the structure. The breakage or debonding of a stiffener, as for instance, changes the load path compared to the healthy structure and increments the load that passes through stiffeners next to the damaged one. Comparing the strains of neighbor stiffeners offers a tool to detect the damage as Takeda et al. demonstrated on flat iso-grid panels [1] and that has been shown also for cylindrical lattice structures [2]. This structural health monitoring, SHM, technique has been studied in different flat space grade composite panels representative for panels manufactured by automatic fiber placement process.

Automatic fiber placement is a nowadays standard manufacturing technique for weight efficient aeronautic and space structures used as for instance for fuselage sections of the Boeing 787 [3], Airbus aircraft structures and Astrium- EADS CASA Espacio manufactured launcher structures [4] enabling complex convex or concave shapes. Skins can be manufactured in any desired lay-up configuration but stiffened structures manufactured with automatic fiber placement are normally manufactured with unidirectional, UD, reinforced stiffeners. The bonded joint between the stiffeners and the skin panels are quite weak because the stiffeners are only bonded to the skins along the area formed by their width and length. No extended foot areas exist like in conventional inverted T, L or Z stiffeners. The automatic fiber placement manufacturing techniques of stiffened panels has been studied before by Astrium-EADS CASA Espacio and grid stiffened single curved panels of 1,8 x 0,9m dimension have been tested at RT and 200ºC [4, 8]. The advantages of these structures have been shown, but a drawback of local stiffener debondings has been detected.

In this work, UD stiffened flat panels, representative for fiber placement processed structures, have been manufactured, have been instrumented with Fiber Bragg Grating Sensors, FBGS, and with distributed optical fiber sensing to study different techniques for detecting debondings of skin- stiffeners and stiffener breakages. The damage detection technique is based on the phenomenon of load distribution. It is expected that a local debonding of a stiffener or a stiffener breakage will cause that more load needs to be transferred through adjacent stiffeners because the damaged stiffener is not able to carry the same load as before the damage occurred.

To study the load distribution between adjacent stiffeners, an anti adhesive film has been laminated just in the stiffener- skin interface in the centre of the mid stiffeners of both stiffened panels 1 and 2. The artificial debonding were 48 mm and 25 mm long in the case of panel 1 and panel 2, respectively. It was expected that the initially debonding promoted by the anti adhesive film will increase somehow gradually with increasing compression load and a gradually increase of the strain distribution would be the consequence. The difference of strain measured on the three stiffeners would be a measure of the growing debonding.

Panel 2 was also instrumented with a continuous optical fiber without FBGSs, for applying the technique of distributed strain measurements. This technique enables to measure the structural strain all along the entire optical fiber with a resolution in the submilimeter range. A technique called Rayleigh backscattering has been applied using the Optical Backscatter Reflectometry, OBR. The objectives of the tests were the same like described before for the FBGSs measurements. The position and

dimension of the artificial debonding and the perfect bond of the rest of the stiffeners has been confirmed by ultrasonic C-scan inspection in panel 1 and 2 prior to the tests. In the case of panel 1, C-scan inspections have been performed also during the test campaign. Compression tests have been performed with the panels to study the possibility to detect the damage due to changes in the relation of the measured strain values in the different positions of the panel.

SPECIMENS

Two different specimens have been manufactured that are representative for structures made in the automatic fiber placement process, although they have been manufactured in this case by hand lay-up. The specimens are stiffened panels with UD reinforced stiffeners and a cuasi-isotropic, c.i., skins layup. The used material is high stiffness fiber and out of autoclave curing resin system. The dimensions of panel 1 and 2 are: 562 x 300mm/ 570 x 300mm, and stiffeners of 4,5mm 6,7mm in width and 15mm /12 mm in height with 85 mm space between stiffeners in both panels. The specimens have been instrumented with three FBGS in each of the three stiffener webs. The egress of the optical fiber from these panels was made in panel 1 with pig tails and in the other with embedded optical small form factor connectors. Panel 2 has been instrumented additionally with embedded optical fibers without sensors to apply the distributed sensing technique. The FBGSs and the optical fiber without sensors are Ormocer coated high strength fibers made by the draw tower process and commercialized from FBGS Technologies company [5, 6]. The excellent performance and highly stable sensitivity of these sensors has been demonstrated before in static and fatigue tests in a wide temperature range from -100ºC to 160ºC [7].
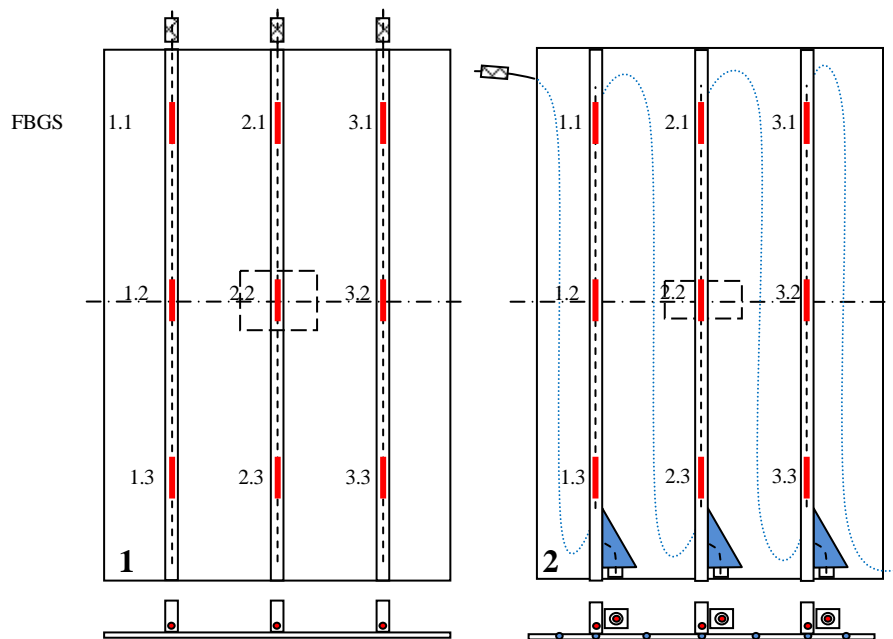

Figure 1. Sketches of the manufactured panels. The interrupted lines represent the optical fibers embedded in the stiffener webs. The fat lines are the FBGSs. The interrupted square in the central stiffener represents the artificial debonding. Left: Panel 1. Right: Panel 2 with embedded optical connectors in the stiffener webs and the distributed sensor fiber embedded in the skin (dotted lone).

MECHANICAL TESTS

The panels have been tested in static compression tests between parallel, non articulated plates until break, figure 2 left. The strains of the panels have been measured with two different equipments. In the case of the FBGS, a Si405 lecture equipment from HBM has been used and for the distributed sensors an OBR4600 sensing equipment from LUNA Innovations, [9, 10]. The test load has been applied in steps of 2 kN with 40s of plateau where the measurements of the distributed sensors have been taken. The measurements in the plateaus are the results of the distributed sensors.
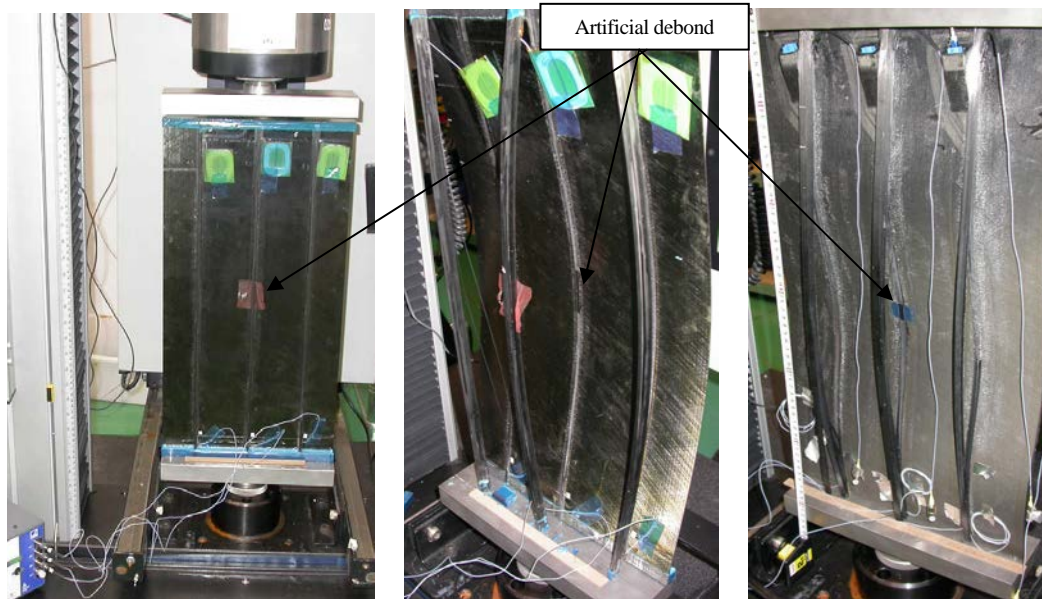

Figure 2. Left: Panel 1 in test rig. Mid.: Panel 1 after breakage. Right: Panel 2 after breakage. Both broken panels are still under a small compression load.

TEST RESULTS

The strain measurements of the FBGSs show in both panels a continuous deformation with increasing load, figure 3. In both panels a general change in the strain distribution can be noticed at elevated loads provoked by the buckling of the skins. No clear change has been noticed along the tests in the strain distribution between the central stiffeners of both panels to their adjacent stiffeners, which could have been an indicator for an increment of the debonding size. The ruptures of both panels were catastrophic with an instantaneous debonding of all the three stiffeners, figure 2 mid and right. In the case of panel 1, a C-scan inspection has been performed not only before testing like in both panels, but also at 50% and 75% of the final rupture load. No increment of the artificial debond has been detected in these inspections. It was expected before the tests that a graduated increment of the central stiffener delamination would occur or that at least only the central stiffener would debond, but the tests of both specimens showed different results. It seems to be possible to state that in this configuration of relative wide stiffeners made of high modulus fiber, the rupture of the panels is catastrophic and no gradual delamination or debonding can be expected. These results are also congruent with the results of the

panel tested in [4] were a wide area of the grid stiffeners delaminated from the skin and with the results of the C-scan inspections of panel 1 that didn't show any increment of the debonding size. Due to this instantaneous rupture without any detectable debonding increase prior to the total rupture, it can be stated that a damage monitoring of this kind of UD stiffened skin panels with embedded FBGS is very difficult.
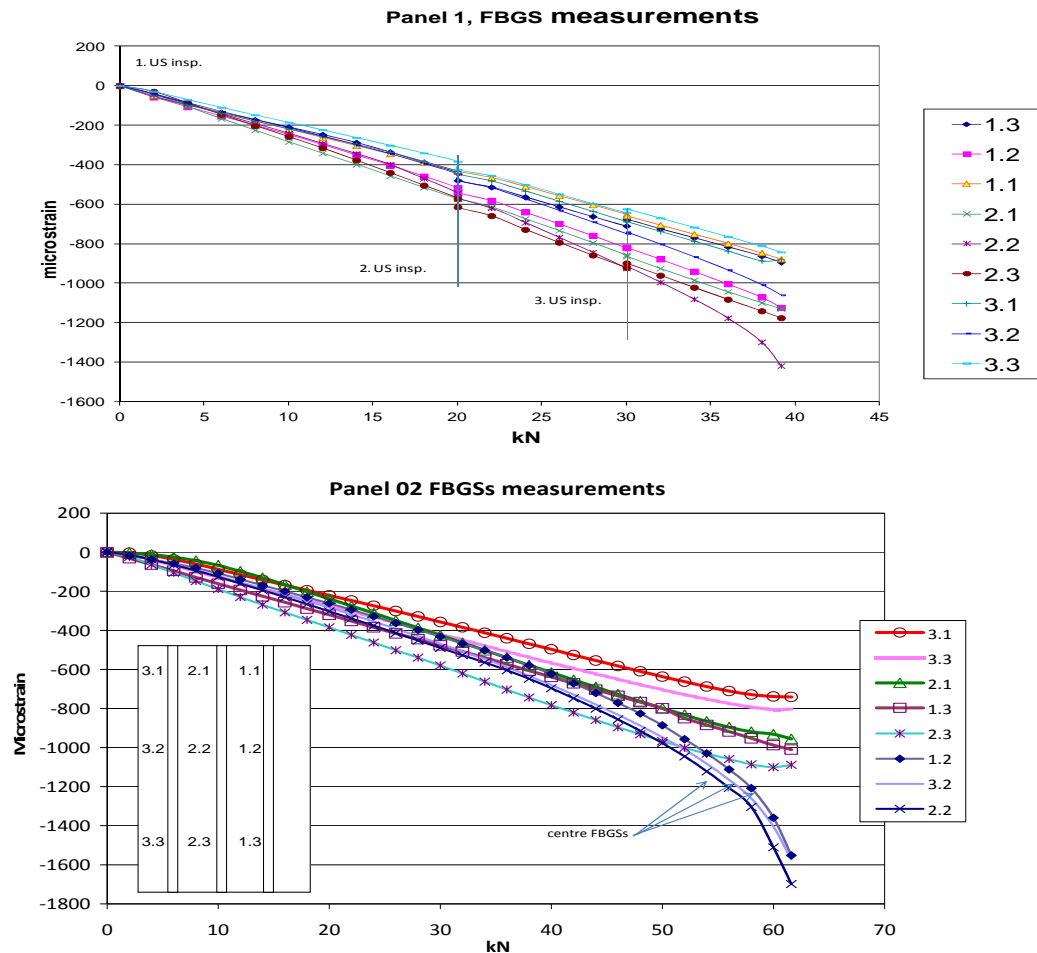

Figure 3. Strain measurements with FBGS embedded in three positions along all three stiffeners in the same position. UP: Panel 1. DOWNn: Panel 2.

In the case of panel 2, the distributed sensors showed a different result. In this case it was possible to detect the artificial debond when increasing load, figure 4 up. Due to the fact that all the fiber length is monitored and that the optical fiber was embedded in the skin of the panel, the debond zone could be detected. With increasing load the zone of the skin just under the debond is not able to transmit the strain as the rest of the skins that are bonded to the stiffeners. At high loads the skins under the delamination starts to buckle and the measured strain values near and just under the delamination show a clear bifurcation that is an indicator for the presence of a debond, figure 4 down. This result could only be achieved with a distributed sensing technique, because it is necessary to compare the strains of small zones with each others. Measuring only in three points of the stiffener is not enough to identify a small delamination in these UD stiffened panels even if the FBGSs would have been embedded in the skin like the distributed sensing optical fiber.
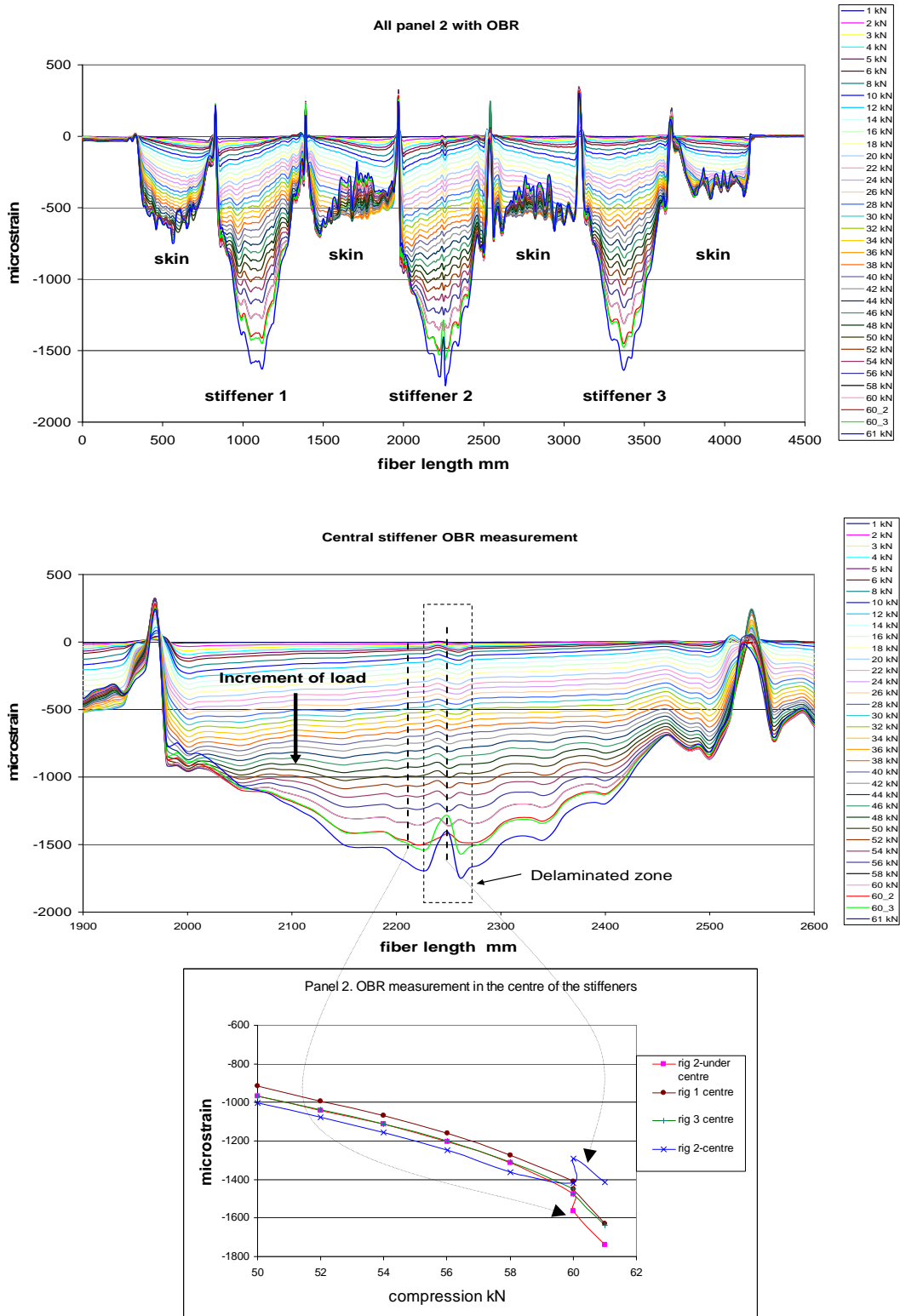
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Figure 4. Mechanical response of panel 2 in compression test before breakage. UP: Distributed sensing strain measurement of the entire panel. MID.: Details of the central stiffener. The delamination can be distinguished with incrementing load. DOWN: Detail close to breakage load. A bifurcation of both measurements of the central stiffener indicates the artificial debond of 25 mm.

A very good agreement has been obtained between the strain measurements of the FBGSs and the distributed sensing, figure 5. The strain values are almost the same until the skin of the panel buckles and slightly different values are measured in both types of sensors. These differences can be explained by different load states in the skin, were the distributed sensing fiber is embedded and the stiffeners were the FBGSs are embedded.
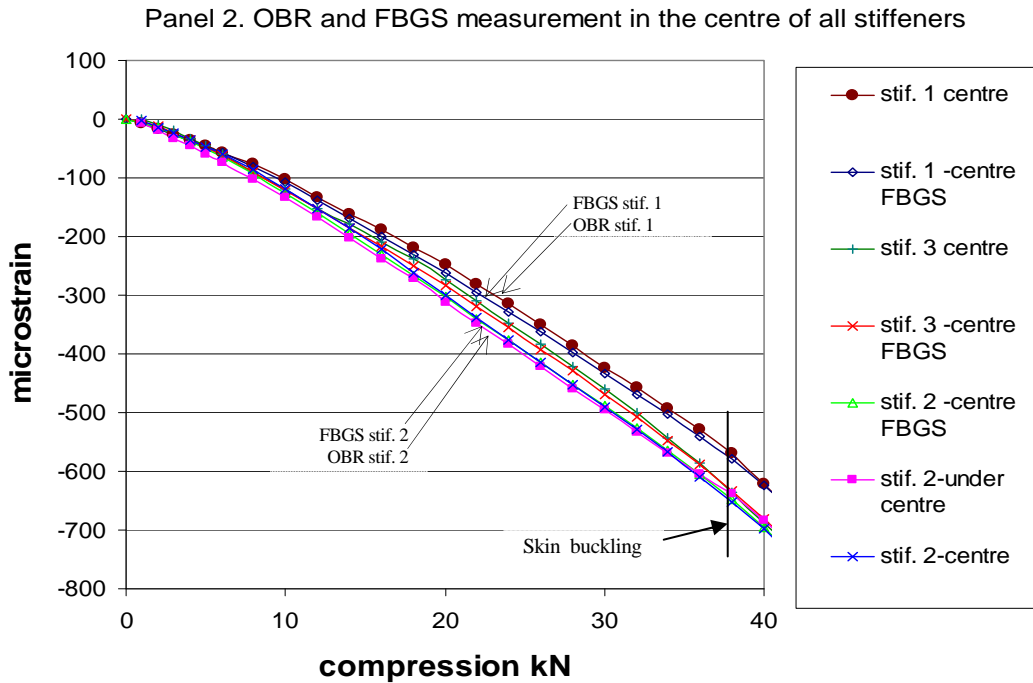

Figure 5. Detail of the strain measurements of the FBGSs and the distributed sensors in panel 2 in the centre of the three stiffeners.

CONCLUSIONS

The very good agreement in strain measurement of embedded FBGSs and embedded optical fiber distributed sensing based on Rayleigh back scattering technique has been demonstrated in compression tests of blade stiffened panels representative for automatic fiber placement manufactured structures. Due to the ability to measure all along the fiber the distributed sensing technique enabled to detect a small 25 mm long debonding in the central stiffener of a panel. The FBGSs were not able to detect this delamination because a detailed comparison between small zones is necessary and the measurements of only three FBGSs in each stiffener web are not enough.

The optical sensor using high strength Ormocer coated fibers showed a good performance during the tests and were still operative when the host structure was already broken.

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