Fiber Optic Based In-Flight Structural Health Monitoring Application Implemented on a Gearbox Support Beam of a Helicopter

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Abstract
A critical crack was identified in the main gearbox support beam of the largest Israeli Air Force (Sikorsky CH53) Helicopter. The crack has developed on the main supporting beam months after it had been repaired. Interestingly, this crack was anomalous in its position and direction and could not have been predicted by conventional Finite Elements (FE) based fatigue analysis. As a necessary step to better understand the actual loading conditions acting on this complex structure and the implications on the growth mechanism of the crack, an in-flight fiber optic based Structural Health Monitoring (SHM) concept was developed. Multiple *Fiber Bragg Grating (FBG) sensors, embedded in composite "Smart Patches", were installed* to fully monitor the structural behavior of the cracked beam during dedicated flight tests. These flight tests varied in their takeoff weights and involved carefully selected maneuvers, designed to have the highest load impacts on the beam. This paper reports the flight data evaluation as part of this SHM concept and introduces the new insights obtained throughout the entire process: from the design stage to the implementation. By analyzing the flight measurements obtained from all smart patches, the factor which most affected the crack growth could be directly inferred. It is expected that this successful experience will potentially lead to broader usage of in-flight SHM systems, which will serve as a preventive, as well as investigative, tool.

Keywords: aerospace, optical fiber sensor, embedded sensor, condition monitoring.

1. INTRODUCTION

Operating aircraft beyond their intended design life results in an increased number of structural service damages. In contrary to manufacturing defects, service damages are particularly challenging because they demand a comprehensive study before conducting corrective maintenance actions. Going by the book, this study should include load characterization and stress analysis by using approximate numerical and/or analytical models of the damaged component. These models then allow the definition of a structural repair with a supportive Non-Destructive Test (NDT) procedure [1-4].
Typically, the approximate numerical/analytical models lead to the proper corrective action. However, sometimes the damage continues to grow and/or additional damages develop nearby to the original damage. For such undesired scenarios, a deeper understanding of the loading condition is necessary in order to ensure the aircraft reliability and safety.
This paper reports the design, manufacturing and flight data evaluation of a Fiber Bragg Grating (FBG) based Structural Health Monitoring (SHM) system, which was designed for the Israeli Air Force (IAF) CH53 Helicopter. Unlike global SHM systems recently reported on

UAVs [5–9], this application aims to investigate the actual loads acting locally on a specific structural component. The motivation for this particular application is described in Section 2. Section 3 reviews the system description and presents the design, manufacturing and calibration of the “Smart Patches” used as the sensing mechanism of the SHM system. Section 4 presents the flight data evaluation and results, while Section 5 offers conclusions and suggestions for future work.

2. MOTIVATION

The gearbox support beams are undoubtedly among the most critical structural component of the Helicopter. Their main role is to transfer the lift force provided by the rotor to the Helicopter frame. Thus, during flight they are subjected to high bending and shear loads. As with many aircraft structural components, these beams are quite complex. Nevertheless, they still preserve the typical arrangement of two Caps and a Web for taking the bending and the shear loads respectively [10,11].

Several years ago two cracks were developed on the web of one of the support beams of the said Helicopter. Apparently, these cracks developed from an existing hole due to fatigue cycling. The Engineering Order (EO) instructed on the application of a metallic bonded repair following the performance of ‘cracks release’. Unfortunately, few years later a new crack has developed at the exact same location. Figure 1 describes the structure of the gear box support beam with a zoom-in onto the damaged area.

As can be observed, the direction of the new crack is horizontal, in contradiction to the Finite Element (FE) based fatigue analysis conducted to justify the previous EO. The FE analysis predicted a high load concentration at the upper area of the crack release (shaped as a banana), and much lower stress levels at the new crack location.

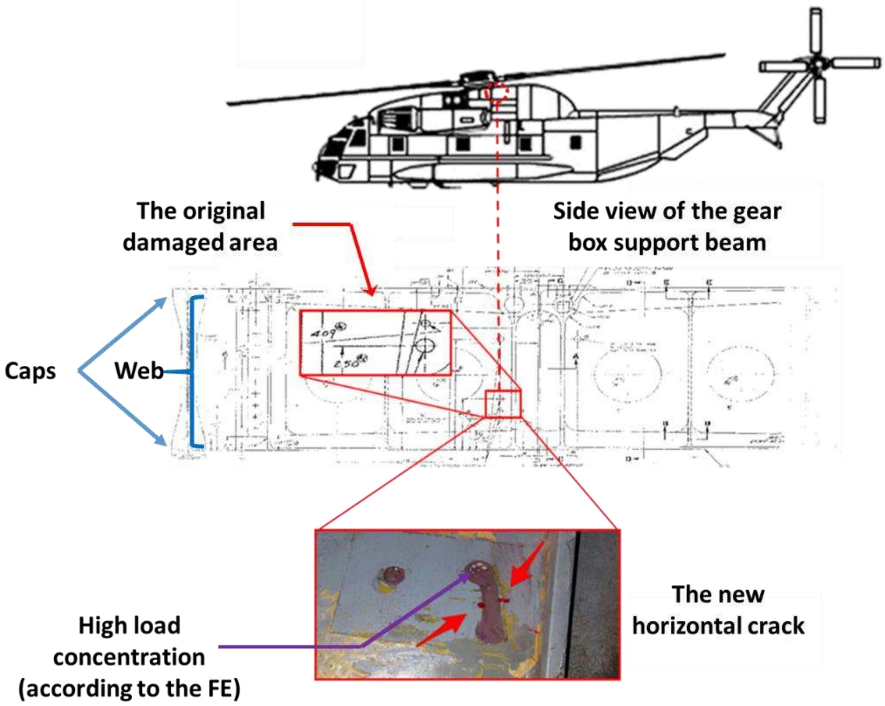

Figure 1: A schematic description of the gearbox support beam structure with a zoom-in onto the damaged area.

The loading conditions applied to the FE models were approximated using fundamental aerodynamic considerations and simplified assumptions. However, the aerodynamics of a

Helicopter and its implications on the gearbox support beam Web are quite complex. The development of an unpredicted crack was both a dangerous sign and a great motivator to adopt the SHM approach described in the next section.

3. SYSTEM DESCRIPTION

As mentioned in the introduction, our SHM concept is based on Fiber Bragg Grating (FBG) sensing. Among the available technologies, FBG appears quite attractive for SHM in general, and for our application in particular. Optical fibers are passive, flexible, insensitive to electromagnetic disturbances, and can function as accurate strain sensors under flight conditions. In addition, the overall technology, including the interrogators, is already quite mature and well-known to be highly reliable [10-11].

A familiar way to integrate FBG sensors with structural components is by initially embedding them in a layer of composite patch and then bonding the patch to the desired location. This concept, reported in many academic sources as "Smart Patch", has been successfully utilized in previous SHM implementations [12-14].

Our system consists of four smart patches, as illustrated in Figure 2(a). Patch #2 and patch #3 are bonded to the exposed side (Figure 2(c)) and to the repaired side (Figure 2(b)) of the Web respectively. These patches contain five FBG sensors each, and are mirrored in their sensor arrangement. The difference in their shape is for visual identification only. Patch #1 contains two FBG sensors, and is not bonded to the structure. While all other patches are sensitive to both strain and temperature, this patch is only sensitive to temperature, and is therefore used for temperature compensation of the readings of the other sensors. Patch #4 is bonded to the other (apparently) healthy support beam at the parallel location. This is done in order to compare the measurements acquired from the two beams - cracked and "healthy". However, this comparison is beyond the scope of this study and has been left for future work.

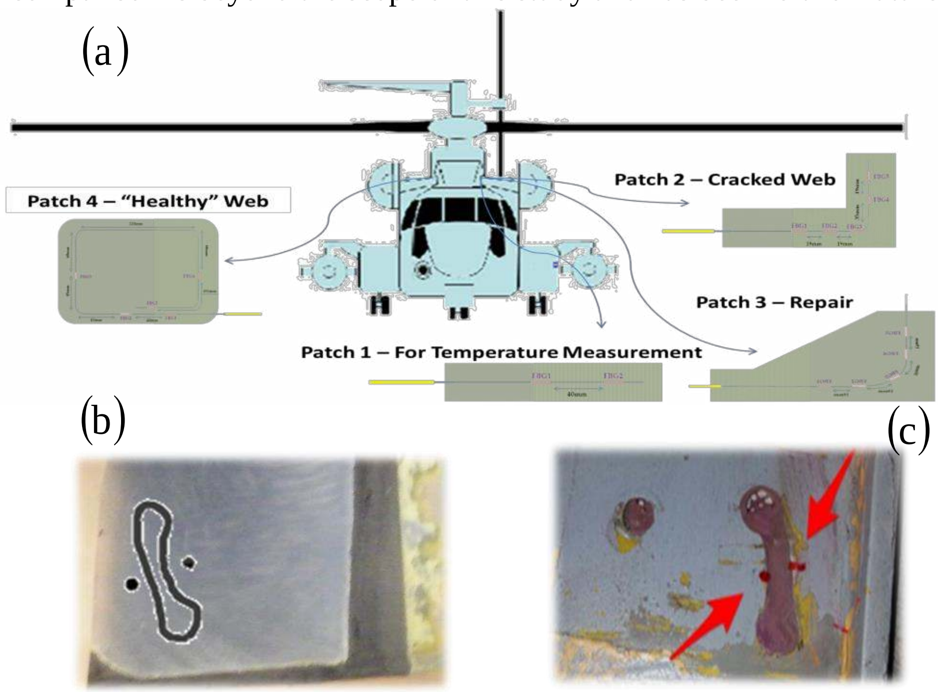

Figure 2: (a) a schematic illustration of the smart patches and their location on the Helicopter; (b) and (c) are respectively the "exposed side" and the "repaired side of the Web.

3.1 Smart Patch Design & Implementation

One of the main advantages of the "Smart Patch" concept over directly implementing the optical sensors to the structure is the accuracy obtained in the sensor arrangement. It is much more convenient to control the sensor arrangement when the process is done in the lab. Moreover, the smart patch can be tested before it is implemented on the aircraft structure.

The manufacturing process of our smart patches can be divided into four stages. First, measurements are taken on the aircraft component to decide on sensor arrangement. Then comes the smart patch design which includes both a sketch of the optical fiber and a sketch of the composite layers. The sketch of the optical fiber contains the FBG wavelengths and the spaces between them, and the sketch of the patch contains dimensions and the estimated path of the optical fiber. The third stage involves the fabrication which is performed in the lab according to the design. Finally, the sensitivity of the FBG sensors need to be calibrated. The gearbox support beams reach relatively high temperatures during flight as a result of the main rotor rotation. As is well known, the FBG sensors are quite sensitive to temperature and therefore this stage is particularly important. The manufacturing process is graphically described in Figure 3.

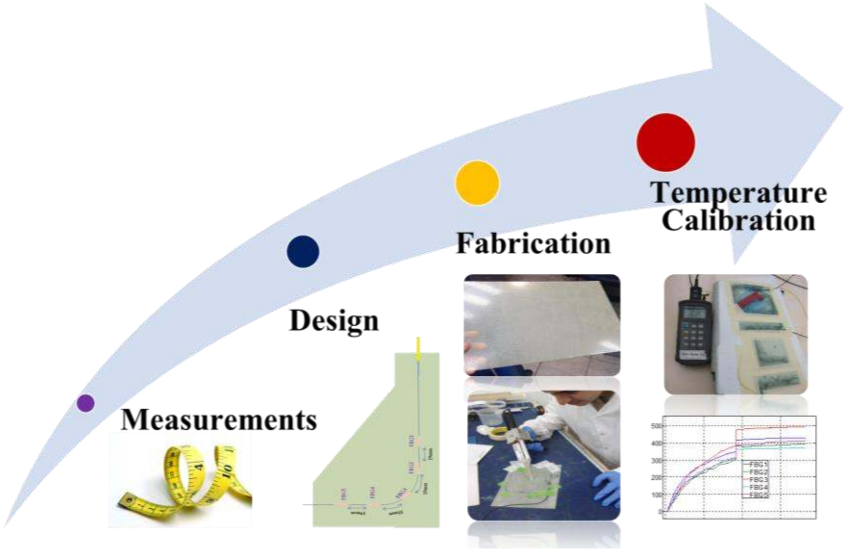

Figure 3: a graphical description of the manufacturing process of our smart patches.

The implementation of the smart patches on the Web is quite similar to that of composite material based structural repairs. Surface preparation is very crucial and therefore must be properly performed. To enhance the curing process, a vacuum pump and a heating blanket were used. Pictures taken at different stages of the implementation are shown in Figure 4.

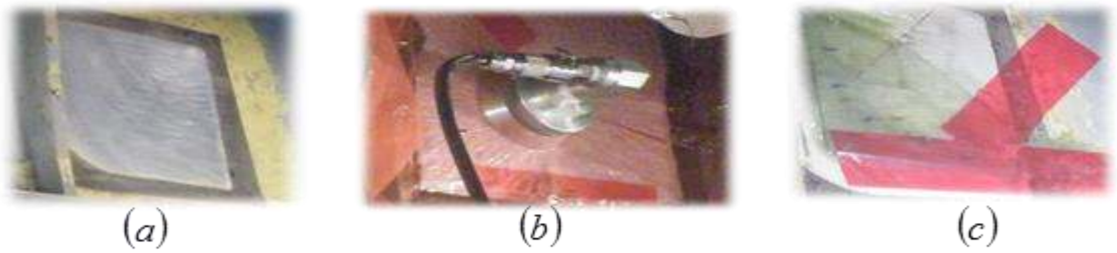

Figure 4: (a) The repaired side of the Web after the surface preparation; (b) the curing process using a vacuum pump and a blanket heater; (c) the bonded smart patch at the end of the process.

4. FLIGHT DATA EVALUATION

After the curing process had been successfully completed, the sensors were recorded during dedicated flight tests. These flight tests varied in their takeoff weights and involved carefully selected maneuvers, designed to have the highest load impacts on the beam. The flight data was analyzed and evaluated "off line" by various data analysis techniques. This study focuses solely on one of these techniques, which is based on comparing sensors placed at different locations to obtain insights into the structural behavior of the Web.

4.1 Comparison of Sensors - Same Smart Patch

In Figure 5, a comparison between the two horizontal sensors placed on patch #2 is presented. These sensors are placed parallel to the crack direction (Figure 5(c)). As can be observed from the raw data (Figure 5(a)) and the graph correlation of FBG1 vs. FBG2 (Figure 5(b)), the readings of the two sensors are similar during the entire flight, indicating a constant strain field in the horizontal direction, a few centimeters from the crack.

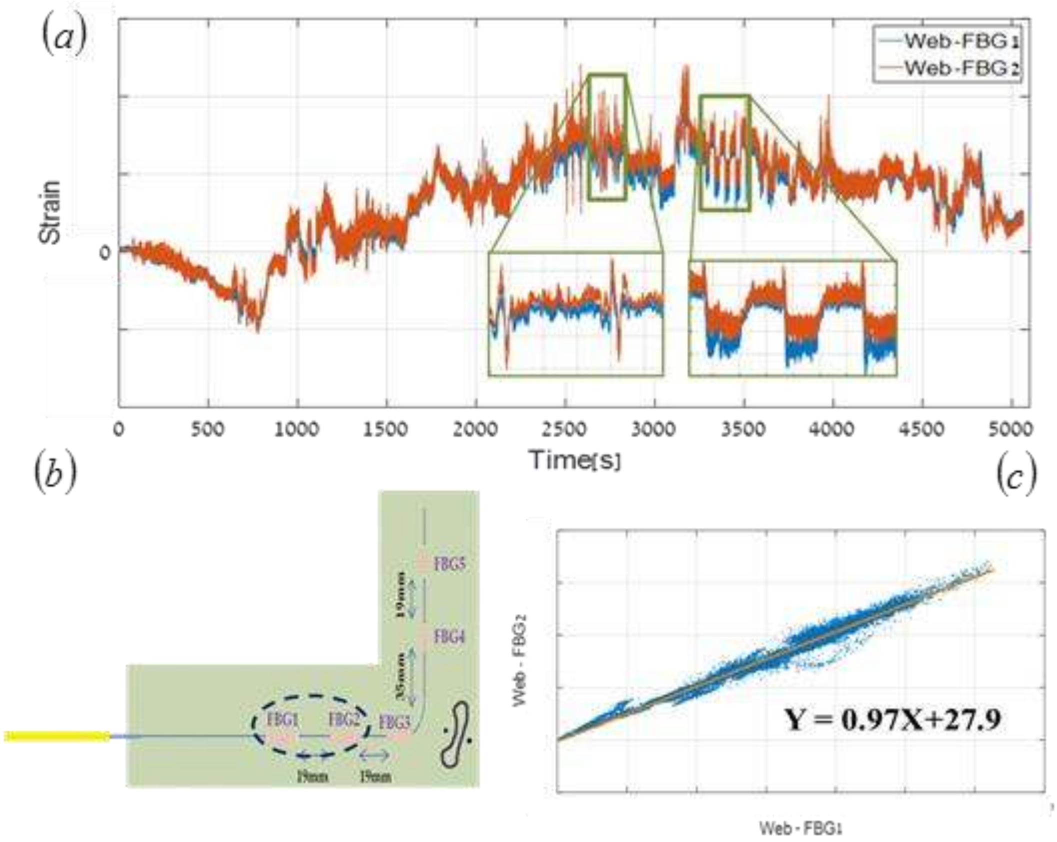

Figure 5: (a) plots of the two horizontal sensors placed on the Patch #2; (b) the exact location of the horizontal sensors on Patch #2; (c) the graph correlation obtained for FBG1 Vs FBG2.

Comparison of other sensors placed in the same direction, whether horizontal or vertical (Figure 6(a)), led to the same conclusion. However, as shown in Figure 6(b)) the correlation between the vertical sensors placed on patch #3 is very scattered. At a first glance, this could hardly be discovered from the raw data. However, after performing a zoom-in, an erroneous FBG5 reading was identified. This fault was investigated to improve our future smart patch implementations.

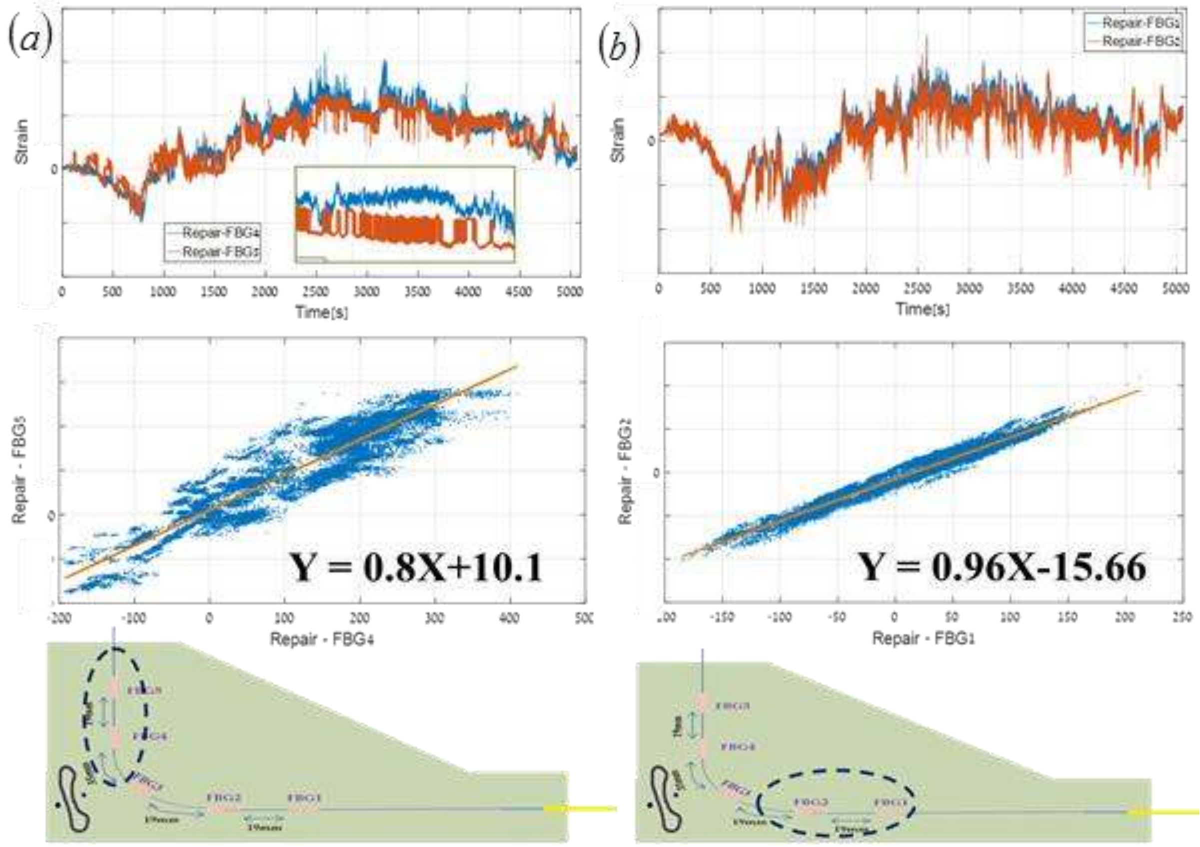

Figure 6: (a) comparison of the two vertical sensors on Patch #3 including their correlation;
(b) comparison of the two horizontal sensors on Patch #3 including their correlation.

4.2 Comparison of Sensors – Different Smart Patches

Tension stresses vertical to the crack are the main contributors to its growth. Therefore, the investigation of the vertical FBG sensors is particularly interesting and may shed light on the development of the crack.

As explained in Section 2, our support beam is most likely subjected to bending and shear loads, which are taken by the two Caps and the Web respectively. If so, the vertical sensors placed in patch #2 and patch #3 should either correlatively measure tension or compression strain. In other words, when a vertical sensor placed on patch #4 is subjected to tension, its counterpart on patch #3 is also subjected to tension and vice versa.

In Figure 7(a), plots of the two vertical sensors placed on Patch #2 and Patch #3 (Figure 7(b)), are illustrated. Unexpectedly, only by observing the plots, one can identify periods of time along the flight where the two vertical sensors are opposite in their sign. Furthermore, by analyzing the appropriate correlations obtained for different maneuvers (Figure 7(c)), there is a clear evidence of local bending of the Web. This local bending is inferred by the negative slopes of the correlation curves, which can be obtained only when one side of the Web is subjected to tension while the other one is subjected to compression. This discovery stands in contradiction to the FE analysis, and was utilized to define the corrective maintenance action.

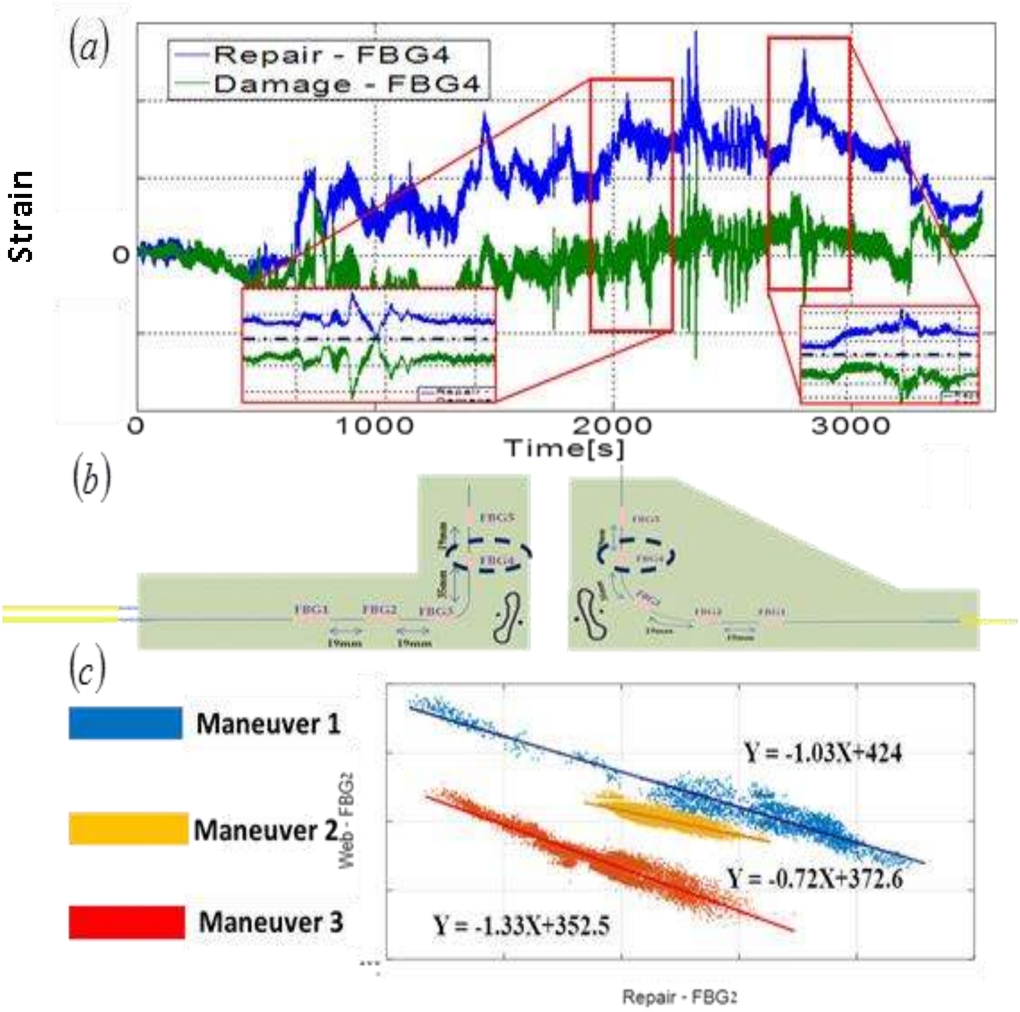

Figure 7: (a) Plots of the two vertical sensors placed on Patch #2 and Patch #3; (b) the exact location of the vertical sensors; (c) Correlations obtained for the two vertical sensors for three different maneuvers.

5. ONCLUSIONS & FUTURE WORK

This paper reported the flight data evaluation as part of a SHM concept, and introduced the new insights which were obtained throughout the entire process. The SHM concept included four carefully designed smart patches, where the readings from their embedded FBG sensors were recorded during dedicated flight tests. The motivation was to fully monitor the actual loading conditions which are induced in the Web of a cracked gearbox support beam during actual flights. Multiple sensors placed at different locations were compared, and thus the structural behavior of the Web was inferred. By analyzing the correlation of two vertical sensors placed on different patches, an unexpected bending of the Web was identified in several maneuvers. This undesired bending of the Web is probably the main contributor for the development of the crack. In the future, the sensors placed on the cracked Web will be compared to the sensors placed on the other Web (Healthy) with the aim to derive additional damage-generating patterns. In addition, the exact relationship between the crack growth rate and the operation of the Helicopter will be investigated by comparing the SHM data and the accurately timed flight maneuver documentation. It is expected that this successful experience will potentially lead to broader usage of in-flight SHM systems, which will serve as a preventive, as well as investigative, tool.

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