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Instrumentation of integrally stiffened composite panel with fiber Bragg grating sensors for vibration measurements

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Abstract

We evaluate the performance of fiber Bragg grating (FBG) sensors for the measurement of dynamic strains in complex composite structures. The particular structure used in this study is an integrally stiffened composite panel for which the stiffeners and skin are fabricated in a single layup and cure process. Surface-mounted FBG sensors are bonded to the panels after curing, whereas embedded FBG sensors are successfully incorporated during the fabrication process. A finite element model was also constructed of the stiffened panel. The panels were subjected to repeated impacts and the post-impact vibration response of the panel was measured through the FBG sensor responses. Little change to the global response of the panel was observed after the repeated impacts, through the dynamic response of the surface-mounted FBGs. Pulsed phase thermography and micro-computer-tomography imaging of the panel confirmed that the damage was localized near the impact locations, producing negligible changes to the global response of the panel. All of the embedded FBG sensors survived the fabrication and multiple impacts; however, as these were embedded close to the neutral axis of the panel, they were not very sensitive to the vibration modes. Excitation of the panel near the first natural frequency did produce a measurable response in the FBG sensors, confirming their functionality.

Keywords: structural health monitoring, fiber Bragg gratings, composite structures

(Some figures may appear in colour only in the online journal)

1. Introduction

With the recent expansion in airframes fabricated from composite materials, a critical need has arisen to develop technologies to monitor their structural integrity. As their failure modes are distinct from those of metallic airframe structures, these technologies must be specific to laminated composite airframes. One direction has been to instrument stiffened composite airframe structures with fiber Bragg grating (FBG) sensors for strain measurements. These measurements have provided information for condition

monitoring of the airframe, impact damage detection, quality assurance during curing of the composite laminates, and buckling of airframe components [1–7]. The main benefit to using FBG sensors is the fact that FBGs can be multiplexed in large numbers on a single optical fiber, significantly reducing the weight of instrumenting the structure with a large number of sensors.

The FBG sensors can be adhered to the surface of the stiffened panels, or embedded directly into the composite laminate during layup of the structural component. Each of these configurations has advantages and disadvantages

relating to the ease of implementation and the quality of the data obtained from the sensors. Surface-adhered FBGs are more easily implemented, do not degrade the structural performance of the airframe and can be more easily replaced in case of sensor failure. However, the strain transfer from the structure to the sensor is generally less effective than for embedded sensors. In addition, surface-mounted sensors can disbond, particularly during cyclic loading, leading to false strain readings. In extreme cases they can miss high strain indicators of damage due to this disbonding [8].

On the other hand, embedded FBG sensors can provide detailed strain information at different depths within the stiffened composite structure, providing a better understanding of the actual structural deformations. Ruzek *et al* [2] demonstrated that surface-mounted and embedded FBG sensors provide significantly different response during buckling of a stiffened panel, presumably due to the thickness variations in the strain field in the stiffeners and skin during buckling. Embedded FBGs require more complex calibration of the strain transfer between the sensor and the surrounding material system, can degrade the long-term performance of the composite material if not embedded carefully, and require complex methods to optimize the sensor placement for expected loadings [9–12]. In addition, the surrounding micro-structure of the composite material can create nonuniform and multi-component strain transfer along the FBG, leading to distortion of the reflected spectrum from the FBG. This distortion is often increased in the presence of impact damage [5, 13, 14].

The strain information obtained from FBG sensors in these applications has generally been applied in three different manners. The first is the use of strain anomalies to detect buckling of the stiffened panel, a critical failure mode in skin-stiffener airframe structures [1, 2, 4–7]. The second approach is to measure the FBG strain due to an acoustic signal in the composite due to propagating Lamb waves, for example, through acoustic emission or active actuation of the structure with piezo-electric (PZT) elements [15]. Such information can then be applied for damage detection and identification within the airframe. The final approach is to use the FBG strain as a function of time for dynamic analysis of the structural behavior including modal analysis to detect delaminations and impact localization [16–20]. It is this third use of the FBG strain information that we will target in this work.

In this paper, we compare the performance of surface-mounted and embedded FBG sensors for the measurement of the vibration response of a composite panel with two integrally fabricated, T-shaped stiffeners. Takeda *et al* [3] previously embedded an optical fiber sensor array at the interface between the stiffener and skin in an integrally stiffened composite panel. Measurements from the array were obtained during the curing process and quasi-static bending of the panel. However, in this work, we will demonstrate the embedment of these sensors into the skin of the panel and evaluate their sensitivity to vibration monitoring of the panel. In particular, the ability of the FBG sensors to survive multiple impacts to the panel will be investigated. Finally, in order to identify and compensate for spectral distortion in the

measurements, the FBG responses are collected with a dynamic, full-spectral interrogator recently developed by the authors [21].

2. Specimen production

Integrally stiffened, carbon fiber-epoxy laminated composite panels were instrumented with FBG sensors and tested during vibration loading in this study. The two T-shaped stringers were integrally cured with the skin panel using vacuum-assisted resin transfer molding (VARTM). Integral curing of the skin and stiffeners reduces the manufacturing operations required and eliminates the need for adhesive joints, therefore increasing the strength of the panel. Preliminary trials were run to identify the specific procedure for the VARTM process until a successful and repeatable production plan for the integrally stiffened panels was obtained.

The dry carbon fiber fabric was first assembled on a waxed metal mold with layers of peel ply and flow media underneath, as shown in figure 1(a). All fabric was uni-directional carbon fiber with a thickness of 0.229 mm [22]. All 8 layer carbon fiber sections noted in the cross-section view followed the stacking sequence $[+45^\circ/-45^\circ/0^\circ/90^\circ]_S$. The resulting skin thickness was therefore 8 layers, the vertical stiffeners thickness was 16 layers and the stiffener flange thickness was 8 layers. Additional layers of peel ply and flow media were added above the carbon fiber laminae and the vertical stiffener metal molds placed on top. The entire assembly was clamped and the molded assembly was then placed on a table with vacuum bagging and release film. After the clamp was removed, vacuum bagging was applied over the mold and sealed with putty tape. The two-part epoxy resin and hardener system (System 2000 epoxy and 2120 hardener, Fibre Glast Developments Corporation) was mixed prior to infusion. The inlet and outlet tubes for resin infusion can be seen in figure 1(b). After full resin infusion, the specimen was left to cure at room temperature for 48 h. Figure 2(a) shows the specimen once removed from the VARTM setup, and figure 2(b) shows the final specimen dimensions. The thickness varied throughout the panel by 0.178 mm. The 8 and 16 layer sections had average thicknesses of 1.19 and 2.39 mm respectively.

The first specimen (specimen 1) utilized surface mounted, polyimide-recoated FBG sensors, which were applied after the specimen was removed from the VARTM setup. The FBG sensors were mounted to the specimen using M-Bond 200 strain gage glue. Before sensor mounting, the surface was prepared with 60 grit sandpaper and cleaned with isopropyl alcohol. The location and orientation of each FBG on specimen 1 is shown in figure 3. The four FBG sensors had Bragg wavelengths, prior to mounting, of 1555.95 nm (A), 1560.13 nm (B), 1564.13 nm (C) and 1568.09 nm (D). FBGs A and C were mounted on the edge of the flange at the transition from the 16 layer to 8 layer panel thickness, while FBGs B and D were mounted on the skin in-between the flanges.

Figure 1. (a) VARTM assembly layup for an integrally stiffened panel. (b) Specimen 1 under vacuum.

Figure 2. (a) Specimen 1 after curing and removal from mold. (b) Final dimensions of specimen 1. All dimensions in mm.

As discussed in the introduction, FBGs can be embedded within the carbon fiber build-up in order to gain insight into the composite inner structure enabling integrated measurements. The other specimens, specimens 2 and 3, therefore contained embedded sensors that were placed during the VARTM fabrication process. The sensors were positioned between layers 4 and 5 of the 8 layer carbon fiber sections that make up the skin, leaving fiber optic cables protruding from the layup for connection to the measurement devices. Figure 4 shows specimen 3 after removal from the VARTM setup, along with the location and orientation of each FBG. The dimensions of these specimens were identical to those of specimen 1. This FBG sensor array was coated with Ormocer during draw tower fabrication. Prior to the full fabrication, a similar optical fiber array was integrated in an 8 layer $[+45^\circ/-45^\circ/0^\circ/90^\circ]_S$ flat panel, using the same VARTM procedure. Figure 5 shows a cross-sectional view of this embedded single-mode silica optical fiber (125 μm bare fiber diameter, 250 μm fiber Ormocer coating diameter). The optical fiber is indeed properly embedded in the middle of the carbon fiber laminate with minimal influence on the surrounding carbon fiber-epoxy composite.

Specimens 2 and 3 contained FBG arrays of 31 sensors, with Bragg reflecting wavelengths ranging from 1530 to

Figure 3. (a) Location of surface-mounted FBG sensors A–D on specimen 1 (top view). All dimensions in mm. Impact locations (1–4) shown as circles. Impacts were applied on the skin surface (surface opposite FBG locations). (b) Detailed view of mounted sensors. Red circles indicate FBG locations.

1590 nm ($\Delta\lambda = 2$ nm) and a 2 cm spatial separation. Figure 6 shows an optical spectrum analyzer read-out measurement from the array in specimen 3, collected using an amplified spontaneous emission (ASE) source and an optical circulator, before and after the embedding process. All sensors were functional after the fabrication and releasing the specimen from the mold, proving the feasibility of integrating a multiplexed array of FBGs using the integrally stiffened, VARTM process. There is however a degradation of the sensing signal ranging from a few dB up to 5 dB. In the higher wavelength range, there is also evidence of residual stresses present in the composite laminate evidenced by the distortion of the individual FBG sensor peaks and indicating potential early failure locations.

3. Experimental methods

For vibration loading of the stiffened panels, each panel was mounted to a vibration table, as shown in figure 7. The vibration table consisted of a stainless steel 61 cm × 61 cm ×

6.1 cm breadboard with a honeycomb core mounted on a single-axis pillow-block assembly. The breadboard was actuated by a PZT stack actuator mounted beneath the platform. Two adjustable turnbuckle-spring biases were mounted on each side of the platform to constrain the motion of the board to small displacements. A low-voltage PZT amplifier provided a 50 V dc offset voltage to the PZT stack. The PZT stack was driven by a function generator, and at full power, had a stroke range of 60 microns $\pm 20\%$ and push force of 1000 N.

The mounting system for the specimen consisted of a set of aluminum base brackets rigidly bolted to the stainless steel breadboard. The specimen was set on top of these base brackets and was clamped down by a pair of aluminum top brackets. Rubber sheets were placed on either side of the specimen surface to better distribute the load on the specimen and prevent local failure of the specimen edges. Although this rubber added some damping to the system, the rubber was sufficiently thin (0.79 mm) such that the specimen edges were considered to be clamped.

An accelerometer was used to characterize the frequency response of both the vibration platform and the stiffened panel

Figure 4. (a) Location of embedded FBG sensors within specimen 3 (top view). All dimensions in mm. Optical fiber shown as a red line. FBGs were spaced at 2 cm intervals along optical fiber. Location of five FBGs in horizontal section are shown ($\lambda_B = 1558, 1560, 1562, 1564, 1566$ nm). Impact locations (1–6) shown as circles. Impacts were applied on the skin surface (surface opposite FBG locations). (b) Specimen 3 after removal from the VARTM setup.

Figure 5. Cross-sectional view of an embedded optical fiber (125 μm diameter single-mode, 250 μm coating diameter) embedded in the 90° direction within an 8 layer $[+45^\circ/-45^\circ/0^\circ/90^\circ]_S$ carbon fiber stacking sequence.

specimens. When mounted to the vibration platform, the accelerometer was bolted to the breadboard. However, for specimen testing, the accelerometer was mounted to the specimen using hot glue.

The full-spectral response in reflection of all FBG sensors in this study was acquired with a dynamic, full-spectral interrogator. Full details of the interrogator and post-processing can be found in Vella *et al* [21]. Figure 8 shows a block diagram of the system. The ASE laser source provides a wide bandwidth lightwave signal that is then amplified by an erbium-doped fiber amplifier. The tunable MEMs filter is driven by a function generator, and powered by a dc power source. By adjusting the driving frequency, the MEMs filter can be set to sweep at different speeds and different wavelength windows. There is an inherent compromise between time resolution, wavelength window and wavelength

Figure 6. Optical spectrum analyzer measurements before and after embedding the FBG array during the VARTM fabrication process. The measurements are relative measurements referenced to the optical broadband source spectrum. FBG sensor spectra above 1580 nm show distortion after embedment.

Figure 7. Stiffened panel specimen mounted on a vibration platform.

Figure 8. Block diagram of the FBG full-spectral interrogator.

resolution. For these tests, the FBG interrogator collected spectral sweeps at 10 kHz as frequency components above 5 kHz were not expected. The number of wavelength points per sweep and bandwidth were adjusted as needed for each specimen.

Impact damage was applied manually to each specimen using an impact hammer. The specimen was then excited at 150 Hz while the sensors were interrogated by the system outlined above. Several impacts were applied to each specimen, as outlined in figures 3(a) and 4(a), with sensor interrogation occurring after each individual impact. All impacts were applied to the skin side of the panels.

4. Specimen quality

Prior to evaluating the impact damage, the quality of the as-fabricated stiffened panels was evaluated by comparing their experimentally determined natural frequencies to those of a numerical model. The stiffened panel was modeled using the finite element method in ANSYS, as shown in figure 9. Both the stringers and skin were modeled with SHELL181 shell elements to reduce the computational cost of the model. The material properties of each ply of these regions was input into the model. The final, converged mesh contained 15 525 shell elements. The particular material properties used for the CFRP material are shown in table 1. The Young's moduli were determined through tensile testing of representative coupons. The Poisson's ratios and mass density were based on reference materials [23, 24]. Finally, as accurate shear moduli for the material were not known, they were found through fitting of the experimentally measured natural frequencies to those of the model. The shear moduli were limited within the range of reference text values until the resulting model natural frequencies were close to the physical specimen results.

The lateral edges of the stiffened panel were considered clamped in the finite element model. Applying the finite element model, eleven natural frequencies were calculated for the specimen below 500 Hz. These frequencies are listed in table 2.

In the experimental setup, the vibration table was driven at frequencies in the range 30–500 Hz, in 1 Hz increments up to 250, and 5 Hz increments above 250 Hz. The accelerometer was first mounted on the vibration platform to measure any resonances of the platform itself. A resonance condition was measured at 134 kHz. The experiment was then repeated with the accelerometer mounted to the specimen. A frequency response curve was thus generated for each specimen from the accelerometer feedback. The resulting natural frequencies for specimen 1 are also listed in table 2. Overall, the model and experimental results compared well; 8 of the 11 natural frequencies predicted by the model had correlating values in the experimental results, within 10 Hz.

The small frequency shifts between the predicted and experimentally measured natural frequencies are likely due to two differences between the model and actual specimens. First, the model had a uniform thickness per ply, whereas the total thickness of different regions in the specimen (with the same number of plies) varied by as much as 0.178 mm. Secondly, the model included a hollow region beneath the stiffeners as can be seen in figure 9(d), while in the actual specimen this area was filled with resin. These two

Figure 9. Finite element model of the stiffened panel. (a) Top view; (b) side view; (c) and (d) closeup of stringer–skin connection.

Table 1. Material properties of carbon-epoxy used in the numerical model.

Symbol	Description	Value
E_1	Young's modulus in fiber direction	15.24 GPa
E_2	Young's modulus 90° to fiber direction	3.10 GPa
E_3	Young's modulus out of plane	3.10 GPa
ν_{12}	Major Poisson's ratio	0.3
ν_{21}	Minor Poisson's ratio	0.061
G_{12}	In-plane shear modulus	6.21 GPa
G_{23}	Out-of-plane shear modulus 1	6.21 GPa
G_{13}	Out-of-plane shear modulus 2	6.21 GPa
P	Mass density	1.60 g cm ⁻³

differences were not considered significant to the later response of the FBG sensors. The predicted natural frequencies not captured experimentally, but seen numerically (modes 3, 4 and 7 in table 2), are likely due to the sensitivity of the accelerometer placement used in experimental testing; the mode shapes corresponding to these frequencies did not produce strong displacements at the three accelerometer locations tested on the specimen. The natural frequency measured in the specimen at 325 Hz but not predicted by the

Table 2. Natural frequencies of the numerical model and physical specimen (specimen 1).

Mode number	Model natural frequencies (Hz)	Experimental natural frequencies (Hz)
1	60.6	56
2	85.9	88
3	184.5	N/A
4	194.2	N/A
—	N/A	325
5	354.7	365
6	376.7	375
7	396.7	N/A
8	435.3	445
9	450.3	455
10	462.2	465
11	479.8	490

model is more difficult to explain. It is potentially a mode induced by an interaction with the specimen and vibration platform that is not modeled in the clamped boundary conditions. Overall, the specimens are considered to be of good

Figure 10. Frequency response curves of the specimens.

quality because of the good correlation between the specimens and the numerical model.

Finally, the repeatability of the manufacturing process was assessed by comparing the resulting natural frequencies for the specimens. Figure 10 shows the frequency response curves for the three specimens (up to 200 Hz). Each of the manufactured specimens shows similar natural frequencies. Note that the peak at 134 Hz is attributed to the resonance condition of the vibration of the table itself.

5. Experimental results

Damage was introduced into each specimen through multiple impacts, applied to the skin side of the specimen at the locations shown in figures 3 and 4. After each impact, the

Figure 11. Impact damage in specimen 1. The numbered images correspond to the respective impact number. Black and white images are micro-CT scans in the regions of the impacts. For impact 2, several micro-CT scans are shown at increasing depth through the laminate skin. The color image is a pulsed-phase thermography image of the entire panel.

Figure 12. FFT of sensors (a) A, (b) B, (c) C, and (d) D peak wavelength shift data during panel excitation at 150 Hz, prior to impacts. Red lines indicate predicted locations of panel modes and excitation harmonics.

dynamic response of the specimen was recorded using the FBG sensors, during excitation of the specimen at a single frequency. While the applied impacts were not repeatable between specimens, the response of the FBG sensors can still be compared qualitatively.

Figure 11 shows images of specimen 1 after all impacts were applied. For this specimen, both micro-computer-tomography (micro-CT) and pulsed phase thermography imaging of the specimen was performed. The micro-CT images indicate that features such as indentation (see impacts 3 and 4) and cracking (see impact 1) were visible on the surface; however, these were limited to the regions immediately under the impacts. The pulsed phase thermography images are particularly sensitive to delamination and other defects in the plane of the laminae. However the color phase image in figure 11 does not show the growth of such delamination from the impact locations for impacts 1, 3, and 4. A small amount (approximately one diameter of the impactor) of growth can be seen at the site of impact 2. These observations were confirmed through the micro-CT images at the locations directly below each impact, also shown in figure 11. With increasing depth we observe a change from pure indentation to cracking at an angle following the principal directions of the graphite fibers on the surface layer. The maximum length of the crack was approximately five times the diameter of the

indentation visible at the surface. From these images we can conclude that, while each impact did induce damage at the impact location, the region of influence of each region did not extend to the location of the surface mounted FBG sensors, even for the case of impact 2. Full imaging of the other specimens was not performed; however, the visible surface indications of damage were similar to those of specimen 1.

For specimen 1, with the surface-mounted FBG sensors, full-spectral interrogation of the FBG sensors was performed after each impact while the specimen was excited at 150 Hz. A peak-tracking algorithm was applied to the time series data for each FBG in order to calculate the Bragg wavelength shift over time. Measuring the full-spectrum of each FBG and then applying the peak-tracking algorithm eliminated measurement errors due to distortion of the FBG spectra (particularly apparent after the later impacts). Finally, a fast Fourier transform (FFT) was calculated for each FBG peak wavelength response. The resolution of all FFT calculations are ± 2.5 Hz.

The FFTs obtained for each FBG, prior to any impacts, are plotted in figure 12. The responses for FBGs B, C, and D clearly show the main resonance at the excitation frequency of 150 Hz. The response of FBG A does not show a dominant frequency component above the noise level. This sensor response did not change after the first two impacts and the

Figure 13. FFT of peak wavelength shift data for sensors (a) B, (b) C and (c) D during panel excitation at 150 Hz after successive impacts. Red lines indicated predicted locations of panel modes and excitation harmonics.

sensor broke after impact 3. Therefore, we conclude that this sensor was bonded poorly to the stiffened panel and could not produce reliable information about the panel response. Fortunately, FBG C was at the same location relative to the stringer, so we could still evaluate the result of FBGs mounted at the skin–stringer intersection. As a final note, FBGs C and D

also detected smaller resonances at higher frequencies (near 185, 300 and 425 Hz for FBG C and near 375 Hz FBG D). The resonances at 178 and 427 Hz for FBG C correspond to the third and eighth mode predicted by the numerical model of the stiffened panel, listed in table 2, while the resonance at 298 Hz is the second harmonic of the excitation frequency.

Figure 14. FFT of simulation results for actual damage: (a) FBG A, (b) FBG B, (c) FBG C, (d) FBG D. The dashed line is FFT prior to impacts; the solid line is the FFT after impact 4.

Figure 15. Simulated extended damage (damage regions shown in green).

Similarly, the resonance at 378 Hz for FBG D corresponds to the sixth predicted mode for the stiffened panel. These locations are also indicated on figures 12(c) and (d).

The full-spectral response of each FBG was then measured after each successive impact, again during excitation of the panel at 150 Hz. The same data analysis was performed for the peak wavelengths, resulting in the FFT plots of figure 13. The response of FBG A is not presented. The other three sensors were all functioning after the final impact. In all cases, the amplitude of the response at the excitation frequency remained strong; however, the other peaks generally diminished with increasing impacts. For FBG C, the peak at the second harmonic of the excitation was present after the first impact, but disappeared from the signal afterwards. Similarly, the responses corresponding to the vibration modes (178 and 427 Hz for FBG C and 375 for FBG D) were no longer present after the first impact.

To compare the measured dynamic responses with the FE model, damage was introduced into the FE by reducing the effective stiffnesses of the elements within the damage regions, as defined by the PPT and micro-CT images in figure 11. The strain component at the location and in the direction of the corresponding FBGs was calculated as a function of time from the simulations. Afterwards, the FFT was calculated for the each strain response and are plotted in figure 14. The same calculation was performed on the

Figure 16. FFT of simulation results for extended damage: (a) FBG A, (b) FBG B, (c) FBG C, (d) FBG D. The dashed line is the FFT prior to impacts; the solid line is the FFT after impact 4.

undamaged simulation and the results are also plotted in figure 14. No noticeable differences are observed in the FFT diagrams before and after the final impact event, consistent with the experimental observations. The micro-CT and thermography images confirmed that the damage was localized, and therefore not likely to significantly change the vibration modes of the panel. Thus, it is assumed that the difference in reduction in resonance peaks is due to a degrading bond condition between the sensors and panel.

To ensure that the model was in fact sensitive to damage scenarios, an artificial level of damage was also applied to the simulations, simply by increasing the affected areas beyond those measured in figure 11. The extended damage areas are shown in figure 15. The resulting FFTs calculated for each strain response (at the same locations) are plotted in figure 16, overlapped with the predicted FFT prior to damage. For this case, we observe changes to the dynamic response of the stiffened panel, particularly in the frequency shift of the 184 Hz resonance to 173 Hz, beyond the 2.5 Hz resolution of the FFT calculations. Further, a strong resonance condition at 491 Hz was measured, also for all four sensors. This could either be a new resonance condition, or the shifting of a condition from an original frequency above 500 Hz. The

resonance at the excitation frequency of 150 Hz remained the same.

The same experiment was performed with specimen 3 with the embedded FBG sensor array. The stiffened panel was impacted on the skin side with six successive impacts, in the locations shown in figure 4. The plate was excited at 150 Hz after each impact and the response of the FBG sensors measured. Due to the fact that the embedded FBG sensors were near the neutral axis of the stiffened panel during vibration, the amplitude of the FBG sensor response was extremely small. Therefore, the FFT calculations were performed with low signal noise and were not useful. A second experiment was repeated after each impact, in which the stiffened panel was excited at 84 Hz, near the panel natural resonance condition that can be seen in the simulations of figure 10. The amplitude of vibration at this frequency is not considered realistic for structural monitoring conditions, but was performed to verify that the embedded sensor array was functioning properly.

Figure 17 plots the frequency response of the sensor with initial Bragg wavelength of 1562 nm, closest to impact 6, measured before all impacts and after impacts 1 and 6. This sensor had the highest signal-to-noise ratio due to its location in the output spectrum of the tunable filter. Prior to impact, we

Figure 17. FFT of an embedded FBG at 1562 nm (a) before impact, (b) after impact 1, (c) after impact 6.

observe the strong resonance condition at the 84 Hz, as well as similar strength responses at 14 and 26 Hz. After the first impact, the resonances at 14 and 26 Hz are still visible; however, the response at 84 Hz has reduced significantly. After impact 6, only the response at 14 Hz is much above the noise level. These results are very different than those of the surface mounted sensors, presumably due to the fact that the sensor is entirely constrained to move with the surrounding material system and the is more strongly affected by damage close to the sensor. The low signal-to-noise ratio prevented a

careful analysis of peak shifts due to damage. However, we do observe a rapid decrease in the amplitude of the resonance peak at 84 Hz with increasing impacts. These results highlight the importance of embedding sensors away from the midplane of the skin for increased sensitivity to vibration. However, the sensor response showed a strong sensitivity to damage well before there was a significant change in the global response of the stiffened panel.

6. Conclusions

In this paper, we demonstrated dynamic measurements of vibration frequencies of an integrally stiffened panel, instrumented with FBG sensors. While the surface-mounted FBG sensors were adhered following a well-known procedure, we demonstrated the successful integration of an FBG sensor array into the skin during the integral layup and cure process. All sensors survived the fabrication process and the subsequent, multiple impacts to the panel, with the exception of one surface-mounted FBG. The surface-mounted sensors were more sensitive to the vibration of the panel, but their responses showed some potential bond degradation between the optical fiber and the panel skin. This potential degradation appeared after the first impact. The embedded sensors were confined by the surrounding material and therefore were not susceptible to disbonding. However, their location near the neutral axis of the panel meant that their sensitivity to vibration was extremely low. When the amplitude of vibration was increased by exciting the panel near its first natural frequency, the measurements from the embedded sensors changed rapidly with increasing impact events.

Ultimately, the response of the surface mounted and embedded FBG sensor arrays would ideally be combined to assess the state of the stiffened panel. The surface-mounted sensors could detect shifts in frequency responses (particularly if the driving frequencies were known), whereas the ratio in vibration amplitudes between the embedded and the surface-mounted sensors could indicate shifts in the depth of the neutral axis. The neutral axis location is an excellent indicator of the extent of damage in laminated plates during out-of-plane bending [14].

Finally, it is important to recognize that at the low damage levels at which structural health monitoring information is useful, the damage-induced changes in the eigenfrequencies of the stiffened panel are extremely small [16, 19]. Therefore advanced pattern recognition techniques are often applied required to extract useful damage identification in noisy data [16, 17]. We did not consider such advanced signal processing in this work; however, the FBG sensor collected here would certainly be applicable as input to these signal processing techniques.

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