Sensor sensitivity studies towards development of impact event detection system for composite laminates and metallic plates

Augustin M.J., Sakthi Sathya, S.R. Viswamurthy, Nitesh Gupta, Ramesh Sundaram
Advanced Composites Division, National Aerospace Laboratories, Bangalore
Email: ngupta@nal.res.in

Abstract: Accidental damages caused by low velocity impact events such as tool drop is a source of concern for designers of composite aircraft structures. Low-velocity impacts can create subsurface damages in a composite structure that can significantly reduce the load-carrying capacity of structure, yet showing barely visible impact damage (BVID). Presently, aerospace structures are designed to be damage tolerant and fail-safe in order to sustain BVID since they are likely to go undetected during periodic manual inspection. A real time impact detection system can result in reduction of direct operating and maintenance cost of the aircraft providing confidence in structural integrity of the structure. This paper describes the studies carried out to understand the sensor behaviour towards the impact event for metal plates and composite laminates. Experimental sensor sensitivity studies carried out for metal plates and composite laminates to determine the sensor response for various radial distance, sensor orientation and impact energy. The paper also presents the development and validation of time-based and strain amplitude based algorithms to identify impact location on a metal plate.

Keywords: Impact Detection, Fibre Bragg Grating, Resistive Strain Gauge, Angular and Strain Sensitivity,

1. INTRODUCTION

Composite materials are finding increasing use as primary structural components in many modern applications due to their high strength-to-weight ratio, formability, and other properties that make them preferable to metals and other conventional engineering materials. However, it is well known that composite materials are highly susceptible to hidden internal flaws i.e. BVID (Barely Visible Impact Damage) which may occur while the structure is subjected to low velocity foreign object impact which includes runway debris, tool drop and blunt impact from ground support equipment. In a composite structure, a low energy impact may not leave any visible sign of the impact on the surface. Underneath the impact site there may be extensive delamination. The damage on the backside of the structure can be significant and extensive, but it may be hidden from view [1]. This clearly underlines the need for a built-in autonomous structural health monitoring (SHM) system capable of detecting such impact events in such defect-critical structures.

An important aspect of any SHM system is the sensor integrated with the structure at critical locations. It is important to study the behaviour of sensors in terms of directional sensitivity, sensing range, nature of the signal acquired etc. for impact events. This will eventually help in designing an appropriate sensor cell/network to detect the impact events in composite structures with minimum possible error. This paper describes the preliminary studies carried out to understand the response of two different strain sensors during an impact event. Impacts were conducted at various incident energies and relative position from the sensors. A comparative study has also been conducted for Resistance Strain Gauges (RSG) and Fibre Bragg Grating (FBG)[2, 3] sensors for the impact tests. In order to design an optimized sensor network for impact detection a detailed understanding of the sensor characteristics is needed in terms of directionality, range of influence, response to impact and after effects of impact on the sensors. As FBG sensors measures the change in wavelength along it length hence its orientation/placement w.r.t. impact location plays a very important role in the measurement and on the algorithm subsequently [5-7]. The outcome of the present work has helped in designing a sensor network for impact detection in metallic plates and composite laminates. The response of the sensor network designed based on the studies further used at laminate level for impact location identification using a strain amplitude based algorithm [4].

2. INSTRUMENTATION

It is highly important to select an acquisition system with high reliability, modularity and with integrated signal conditioning. In order to meet such a requirement a dedicated PXIe (PCI extensions for Instrumentation) system from National Instruments programmed in LabVIEW[8] was implemented for Resistance Strain Gauge data acquisition. The NI PXIe-4331 simultaneous bridge input module housed in the NI PXIe 1062Q chassis provides integrated data acquisition and signal conditioning for bridge-based sensors with software-selectable shunt calibration per channel [9].

Smart Fibers Wx-M was selected for the data acquisition from FBG. This system will take the input from the FBG sensors in terms of wavelengths (based on strain on structure) and then send this information computer over Ethernet using UDP/IP protocol. It possesses variable sampling frequency from 2.5 kHz to 20 kHz with decreased sensor per channel.

The instrumentation scheme for the experimental study is presented in Figure 2-1. In-house developed software triggered data acquisition software was developed for the NI PXIe. As Wx-M comes with OEM software, data processing software was developed for extraction of impact data and further post-processing. Figure 2-2 shows the Front panel of the GUI based software developed for data acquisition and analysis.
3 STUDIES ON METAL PLATE

This study involves a lot of experimental work which will increase the cost and time. Hence numerical simulation was done to reduce the cost and time. The numerical simulations were verified with experimental results.

3.1 Numerical simulation

The present problem involves two parts in modelling namely, impactor and plate. The impactor considered for the present study is a solid rigid ball of radius 8 mm and weight 5 Kg. The plates, made of steel, are square 230 mm x 230 mm x 6 mm. The impactor is assumed to be almost rigid and the R3D4 elements are chosen for modeling the projectile. The surface of the impactor is considered as a master surface while the predetermined contact surface of the laminate is assumed to be slave. To discretize the laminate, 3D brick elements C3D8R, having 8-node is employed in Abaqus/Explicit (Figure 3-1).

3.2 Experimental studies

To study the behavior of sensor response with orientation and distance, impact studies were carried out on a 230mm X 230mm X 6mm steel plate. A total of 32 strain gages (16 pairs of 0-90 rosettes) were bonded to one side of the steel plate (Figure 3-4). The plate was impacted on the same side.

Impact tests were carried out on the plate (10J impact energy at the center of the plate) and strain gauge data were recorded on NI PXIe. Figure 3-5 shows the response of SG1, SG2, and SG9 & SG10 across 4 different trials. Results confirm that the impact tests are fairly repeatable.
Figure 3-5 Response of strain gauges during impact at 10J for different trials

Figure 3-6 presents a comparison of the response of strain gages placed symmetrically about the impact location for two different trials.

Figure 3-6 Response of strain gauges placed 20mm from impact location for 10J impact

Figure 3-6 confirms that sensors at the same distance and orientation w.r.t the impact location respond alike to impact across different trials. The difference in responses of the two sensor sets can be seen in the magnitude of the strain. Also it can be noted that the responses are symmetrical as expected by the theory. Impact tests were also carried out at 5J the results are shown in Figure 3-7

Figure 3-7 Response of transversely placed sensors for 5J impact

It is noteworthy to see that the amplitude of the strain measured for different energy levels show a significant change. The strains obtained in tests values were compared with numerical simulation carried out for the same as presented in Figure 3-8.

Figure 3-7 Response of transversely placed sensors for 5J impact

Figure 3-8 Comparison of Numerical Simulation with Experimental data with 10J impact

It shows that there is good match in the duration of impact between test and simulation. The strain values from simulation are comparatively less. The reason for this could be that the boundary conditions as existed during the tests were not simulated properly. And also the steel plate used for the test might not have the standard material property. This shows that there is a necessary to do little modifications in the FE simulation.

Angular and radial sensitivity for the strain sensors towards impact were first studied on steel plate. The strain sensors were surface bonded at the centre of a steel plate of size 540mm x 370mm x 8mm as shown in Figure 3-9. After fixing it on the fixture, the available window for the impact was 490mm x 320mm. Impacts with energy 4J were carried out from 0 to 180° azimuth at steps of 10° each.

Figure 3-9 Sensor schematics and steel plate

Impact tests were repeated for radial distances of 80mm, 100mm and 120mm. The peak absolute value of the strain from the Strain VS time data was picked up for each angle using a LabVIEW program “Range VIEW” and normalized curves are plotted as shown in Figure 3-10

Figure 3-10 Normalized Strain amplitude vs. azimuth for different radii

It can be seen that there exists angular dependency in the strain response and between 60° and 130° the strain variation variations are within 0.2.
4. STUDIES ON COMPOSITE LAMINATE

Angular and radial sensitivity studies were carried out on composite plates of different size. In this study, sensors were surface bonded to both the sides of the laminate and impact tests were carried out on both the sides. Three different laminates were considered in this study: (a) 540mm x 370mm x 2.25mm, (b) 540mm x 370mm x 2.50mm and (c) 230mm x 230mm x 5mm (Figure 4-1).

Figure 4-1 Composite laminates used for the study (a) 2.50 mm thick (b) 2.25mm thick (c) 5mm thick

Composite laminates of size 540mm x 370mm x 2.50mm were surface bonded with FBG and RSG at the center (245, 160) This laminate was impacted with energies 1J and 2J form 0° to 180° with 10° step in a semicircle of radius 80mm. The side of the laminate bonded with FBGs was impacted first. Next, the plate was removed and reversed. Impact tests were then conducted on the side bonded with RSGs. In both cases, data from both FBGs and RSGs were recorded for all impacts. Figure 4-2 presents the variation of normalized strain with azimuth for strain sensors at the top (same side of impact). Figure 4-3 presents the variation of normalized strain with azimuth for sensors at the bottom (other side of impact). It can be seen that, compared to the sensors at the top, the sensors at the bottom have less angular dependency over the angular range of 60° to 130°. The FBG and RSG behavior are in agreement and is repeatable over different energies. After the impact tests, the laminate was subjected to non-destructive evaluation such as ultrasonic A-scan and infrared thermography. No hidden damages were found from these inspections.

Figure 4-2 Normalized strain vs. azimuth for sensors at top

The tests were repeated with the laminate 540mm x 370mm x 2.25mm with sensors configuration as in the previous test. Impact tests were carried out at 2J energy at radius 70 mm, 85mm and 100mm. The variation of normalized strain with azimuth for impacts tests where the FBG sensors were bonded to the bottom side of the laminate is shown in Figure 4-4.

Figure 4-3 Normalized strain vs. azimuth for sensors at bottom

It can be observed that the profile remains mostly the same. The behaviour of the sensors when kept on the same side as impact is shown in Figures 4-6 and 4-7.

Figure 4-4 Normalized strain vs. azimuth for FBG sensors at bottom

Figure 4-5 Normalized strain vs. azimuth for RSG sensors at bottom

Figure 4-6 Normalized strain vs. azimuth for FBG sensors at top

Comparing with the previous test it can be seen that response characteristics of the FBG and RSG remain the same.

Figure 4-7 Normalized strain vs. azimuth for RSG sensors at top
Strain response for impact on 230mm x 230mm X 5mm laminate with RSG at the centre is shown in Figure 4-8 and 4-9. These results show that angular response of the FBG and RSG surface bonded on the composite laminate towards impact are same.

Studies were also carried out with strain rosette (0-90) on 540mm x 370mm x 2.50mm composite laminate with impacts of 2J from 0° to 360°. The results are shown in the Figure 4.10.

This response can be used for deciding the sensor orientation and developing algorithms for impact location estimation.

5. SENSOR NET DESIGN AND ALGORITHM IMPLEMENTATION

Based on the directional characteristics of FBG and RSG, a network of sensors were formed on the steel plate (490mm x 320mm x 6mm) as shown in Figure 5-1. The shaded region represents the active zone where sensors are sensitive towards impact.

5.1 Amplitude based Algorithm

The main idea behind this localization algorithm is to locate damage based on the fact that the maximum strain amplitude increases when an impact is located closer to a sensor [2]. From the time vs strain data the relative strain is calculated by using the absolute strain amplitude as in Equation 1

\[ r_{ij} = \frac{e_j}{e_i + e_j} \]  

Where \( e_i \) and \( e_j \) are the absolute maximum strain of the \( i^{th} \) and \( j^{th} \) sensor, respectively.

The Euclidian distance between two sensors is computed as in Equation 2 and 3

\[ \theta_i = \tan^{-1}\left(\frac{y_j - y_i}{x_j - x_i}\right) \]  

\[ d_{ij} = \sqrt{((x_j - x_i)^2 + (y_j - y_i)^2)} \]

The relative impact position w.r.t these two sensors are calculated using equation 4 and 5

\[ (I_{i})_x = x_i \times r_{ij} \times d_{ij} \times \cos \theta_i \]  

\[ (I_{i})_y = y_i \times r_{ij} \times d_{ij} \times \cos \theta_i \]

The sum of the absolute maximum strains measured by the \( i^{th} \) and \( j^{th} \) sensors

\[ M_k = e_i + e_j \]

In order to accurately predict the location of impact, the relative location points with higher strain magnitudes have to be selected. A selection process is formulated in which the minimum number of these relative location points with the highest strain magnitudes is selected as per condition

\[ \sum_{k=1}^{n} M_k \geq \alpha \times \sum_{k=1}^{m} M_k \]

Where \( n \) is the total number of relative location points, \( m \) number of optimal number of points and \( \alpha \) is a tuning parameter which depends on both the number of sensors and also the geometry (curvature) of the given structure. Proper selection of \( \alpha \) value results in good estimation of impact location. The impact location is estimated as in Equation 8
\[ X_{\text{impact}}, Y_{\text{impact}} = \left[ \frac{\sum_{j=1}^{m} I_{y_j}}{m}, \frac{\sum_{j=1}^{m} I_{x_j}}{m} \right] \] (8)

Estimation of the impact location based on strain amplitude based algorithm with \( \alpha \) value 0.6 is shown in Figure 5-2.

Figure 5-2 Impact location estimation using amplitude based algorithm (with \( \alpha = 0.6 \))

A study of influence of \( \alpha \)-value on impact location estimation was also carried out. It was concluded that \( \alpha \) plays a key role in the accuracy of estimation. The value of \( \alpha \) need to be chosen based on the impact location which in the actual scenario is random and unknown. Based on the experimental evidence, we propose that the mean of normalized absolute strain will be a good choice for \( \alpha \). This is also implemented in the algorithm and the results obtained using the automated \( \alpha \) selection algorithm is shown in Figure 5-3.

Figure 5-3 Impact location estimation using amplitude based algorithm (with automatic selection of \( \alpha \))

It is seen that the choice of \( \alpha \) as mean of the normalized absolute strain gives better accuracy compared to the choice of fixed value for \( \alpha \).

5 CONCLUSIONS

The angular and radial strain sensitivity of RSG and FBG sensors towards impact events on steel plate and composite laminates were studied. The results from sensitivity studies are used to design a sensor network for detection and locating impact loads. A sensor network constituting four FBG sensors was designed based on the angular sensitivity studies and a strain amplitude based algorithm was implemented in LabVIEW for the impact location estimation. Based on the experimental studies and the results it can be summarized that the selection of \( \alpha \) -value as mean of normalized strain amplitude lead to improved identification of impact location as compared to the fixed value of \( \alpha \).

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