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Strain Sensor's Network for Low-Velocity Impact Location Estimation on Carbon Reinforced Fiber Plastic Structures: Part-I

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In this work, we have investigated the strain response (angular/spatial) from fiber Bragg grating (FBG) sensor & resistance strain gauge (RSG) sensors bonded to the composite structure due to the projectile low velocity impact (LVI). The number of sensor & its orientating has been optimized based on such experimental data and designed an optimum sensor network for faithful LVI detection. In order to study the efficacy of the sensor network, an impact localization algorithm based on peak strain amplitude from the sensor bonded to the structure was used in this study. Further the detection efficiency of the algorithm has been improved using weighted average value around the peak amplitude of strain experienced by the sensor. We found that for the high energy (~35 J) LVI the maximum distance error (Euclidian distance) was 50 mm for 80% of total trail case. Furthermore, we have developed and compared the relative performance of the algorithm cited in the literature, will be presented in PART-II of the same Journal.

Keywords: Impact location estimation, Fiber Bragg Grating (FBG), Resistance Strain Gauges (RSG), Structural Health Monitoring (SHM)

1 Introduction

Composite aircraft structures are susceptible to low-velocity impact (LVI) induced damages which causes barely visible impact damage (BVID) on the structure. These damages can result in a significant reduction of the load-carrying capacity of the structure. A system that can notify the occurrence of an impact event along with location and severity could result in the reduction of maintenance cost of aircraft and provide confidence in its structural integrity[1].

Presently, the damage tolerant design makes the structure to sustain BVID since they may go undetected during scheduled inspections. Currently, detection of this type of damage requires the use of specialized non-destructive evaluation (NDE) approaches such as acoustic emission, thermography[2] and ultrasonic scanning[3].

There is a requirement of detecting the impact as and when it happens and reporting the location and its severity of the impact to the maintenance center so that inspection can be carried based on the requirement, instead of the periodic maintenance. Also as the location information as available the inspection can be carried out in a faster and efficient manner. As impact events are random in nature, in both time domain (uncertain when it will occur) and spatial domain (where it will occur), the challenge is to develop a smart impact monitoring system, which will remain active to report the impact event on the structure. The system will comprise of (a) Sensors integrated with the structure (b) Data Acquisition system capable of capturing the impact event (c) Algorithms capable estimating the location (d) Software for the efficient data acquisition. Work carried out towards strain sensor based impact monitoring system development, and its validation on the composite structures is being discussed in this paper.

Various sensor network using resistive strain gauges (RSG) [4,5], Piezo electric sensors[6-9], Fiber Optic Sensors (FOS)[10-14] were suggested in the literature. Passive detection[15-17] schemes are being generally being used for the identification of the location, and active sensing schemes [18-19] are being used the estimation of damage. Passive detection scheme uses sensor response[20] during the impact event and while active sensing uses the external excitation and sensing the response of the structure for the location and damage estimation. PZT based actuation and sensing

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for lamb wave[21-23] is one of the most discussed methods by various authors for active sensing.

The passive detection schemes need various algorithms for the estimation of the location and severity of the impact and impact-induced damage. GPS based algorithms such as trilateration and triangulation[23], strain amplitude based algorithms[24], cross correlation[25]signal processing methods combined with Artificial Neural Network[26,27,] Convolutional Neural Network[28] *etc*. are reported for the estimation of the detection and estimation of impact. The GPS based algorithms rely on the accurate measurement of the time of arrival (TOA) or Time Difference of Arrival (TDOA). The majority of methods in this area often require substantial data for training, and additionally, these methods have been tested for relatively simple plate-like structures. Among the various sensors, Fiber Bragg Grating Sensors is the most preferred sensor[29] for aerospace applications due to its small size, lightweight, immunity to electromagnetic interference.

This work, describes the studies carried out to understand the strain response Fiber Bragg Grating (FBG) and Resistance Strain Gauge (RSG) sensors during an impact event and subsequent design of a sensor network for a composite laminate. FBG sensors measure the change in wavelength along their length[30]. The orientation of the sensors with respect to impact location plays a very important role in measurements and on subsequent algorithms which relies on the strain response. Experimental studies on the sensor characteristics in terms of directionality, range of influence, response to impact event, and effects of impact on sensors were carried out. The studies lead to the design an optimized sensor network, which was used further at a laminate level to identify the impact location, using modified strain amplitude-based algorithm. The algorithm uses the strain response with sensors with random orientation. As this algorithm uses the strain amplitudes it is required to position / make a sensor network capable of capturing the strain effectively so that it leads to the better prediction. Also the algorithm uses a tuning parameter α which is arbitrarily chosen and is fixed. We have proposed that proper choice of the α (based on the geometry and sensor location) can lead to better estimations. Studies has been carried out to find out an optimum value α, gave better accuracy. In this context we would like to mention that we have developed two different algorithms for impact localization. The algorithm development, relative performance of the developed algorithm & algorithm cited in the literature, will be presented as "Strain Sensor's Network for Low-Velocity Impact location estimation on Carbon Reinforced Fiber Plastic Structures: Part-II" in the same Journal (if accepted).

The work is organized as follow: Section 2 describes instrumentation for experimental studies, Section 3 is about sensor response studies which include center impact and response at different location & angular and radial sensitivity studies. Section 4 discuss the sensor network design for impact location estimation, strain scan based algorithm in Section 5. Validation using high energy impact discuss in Section 6 followed by conclusion in Section 7.

2 Instrumentation for experimental studies

The instrumentation scheme for the experimental study is presented in Fig. 1.

The in-house developed portable drop tower consists of drop weight, whose mass can be adjusted between 3 to 9 kg with a hemispherical tup at one end have been used for carrying out the impact tests. The mass with tup falls through guides (very minimal friction) from different heights, calibrated for energy levels. A rebound catcher mechanism is being implemented to prevent multiple impacts. To capture the strain response from the structure during the FBG and RSG, sensors and associated instrumentation for the data acquisition have been used.

A PXIe based instrumentation systems from National Instruments was used for the data acquisition from the Resistance Strain Gauge (RSG) sensors. NI PXIe Chassis 1062Q with 8 channel NI PXIe 4331 strain modules[31] were used in acquiring the data from the strain sensors. This card provides the necessary signal conditioning and calibration. This

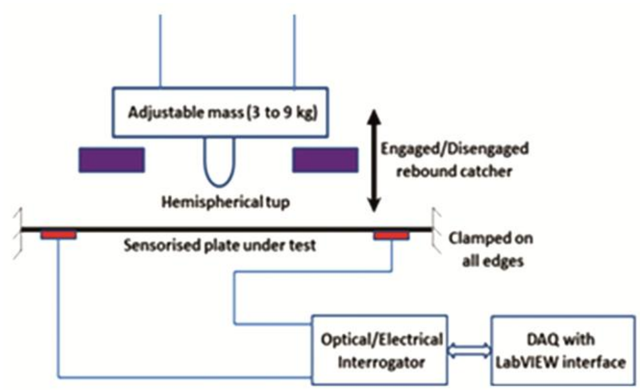


Fig. 1 — Experimental study setup used for impact detection on the structure

instrumentation schemes is modular and scalable and can acquire strains in the rate of 100 KHz sampling rate. For the data acquisition a software triggered data acquisition to capture the data around the impact response peak was developed in Lab VIEW and was used in the study.

FBG sensors are also used in the study. FBG sensor is a short length of a single mode fiber where a periodic variation of refractive index is made at the core for the fiber. This section of the fiber reflects a particular wavelength of the broadband source of light launched into the fiber satisfying the Bragg diffraction condition given as[32]:

$$\lambda_B = 2\, n_{eff} \Lambda \qquad \ldots (1)$$

where, λ_B being Bragg wavelength, Λ period of diffraction grating, n_{eff} *is the* effective refraction index.FBG respond to both strain and temperature in a linear fashion. When then applied load or the temperature changes the reflected Bragg wavelength shift is given by[32]:

$$\Delta\lambda_B = C_1 \Delta\varepsilon + C_2 \Delta \qquad \ldots (2)$$

where, C_1 is the strain sensitivity (pm/με) & C_2 is the temperature sensitivity (pm/°C).The typical values of C_1 and $C_2$are 1.23 pm/με and 10 pm/°C[32].

In this work, we have used Smart fibers Wx-m interrogator[33] system which works on the principle of swept laser interrogation. This four channel system can be configured through the Smart soft application suite for acquiring the sensor data at the rate of 20 kHz, with 5 nm interrogation window. FBG sensors with center wavelength falling in the interrogation window is used in the study. Single FBG sensors are used whose center wavelength between 1536 -1555 nm, with peak reflectivity greater than 90 % with full width at half maximum (FWHM) greater than or equal to 0.25 with polyamide coating.

3 Sensor response studies

Ideally to detect impact events it is required to have sensors everywhere in the structure, which is not feasible. Therefore, it requires placement of minimum number of sensors that can capture the strain efficiently at critical locations. At critical locations to capture the strain amplitude efficiently it is required to bond the sensor in the proper orientation. In this section the experimental studies carried out towards understanding the behavior of center impact and its response at different location and angular and radial sensitivity which is critical needs for designing an appropriate sensor cell/network to monitor the impact events in structures.

3.1 Center impact and response at different location

A steel plate of size a 230x230x6mm^3 with strain 32 strain gages (16 pairs of 0°- 90° rosettes) were bonded to one side of the steel plate as shown in Fig. 2. The impact tests were carried at the center of the plate.

Fig. 3(a-d) shows that the strain response from the sensors at same distance and orientation respond in the same manner. The strain response from SG2, SG9, SG18 and SG25 which are oriented perpendicular and is at same distance from the center of the impact. Same observation can be made for the other set of strain sensors at same location with same orientation. Again the strain response from SG1, SG10, SG17 and SG 26 which are oriented in line and is at same distance from the center of the impact with 10 J energy. It can be seen that response of the sensors from same location with different orientation is different in magnitude.

The strain responses from the transverse sensors for 5J impact for three different trials are shown in Fig. 4.

One can note that strain amplitude is less for the low energy impact as compared to Fig. 3. Thus, to use the strain response for detecting the impact location it is required to have a comprehensive understanding on the strain response in terms of directionality, range of influence, response to impact and after effects of impact on the sensors. This can help in making an optimized sensor network for monitoring the impact location.

3.2 Angular and radial sensitivity studies

The angular and radial sensitivity, experimental studies were carried out on composite plates of

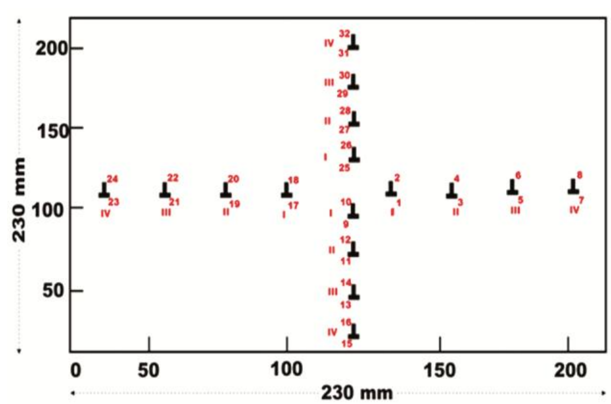


Fig. 2 — Locations of the strain gauges in the steel plate of size (230x230x6 mm)

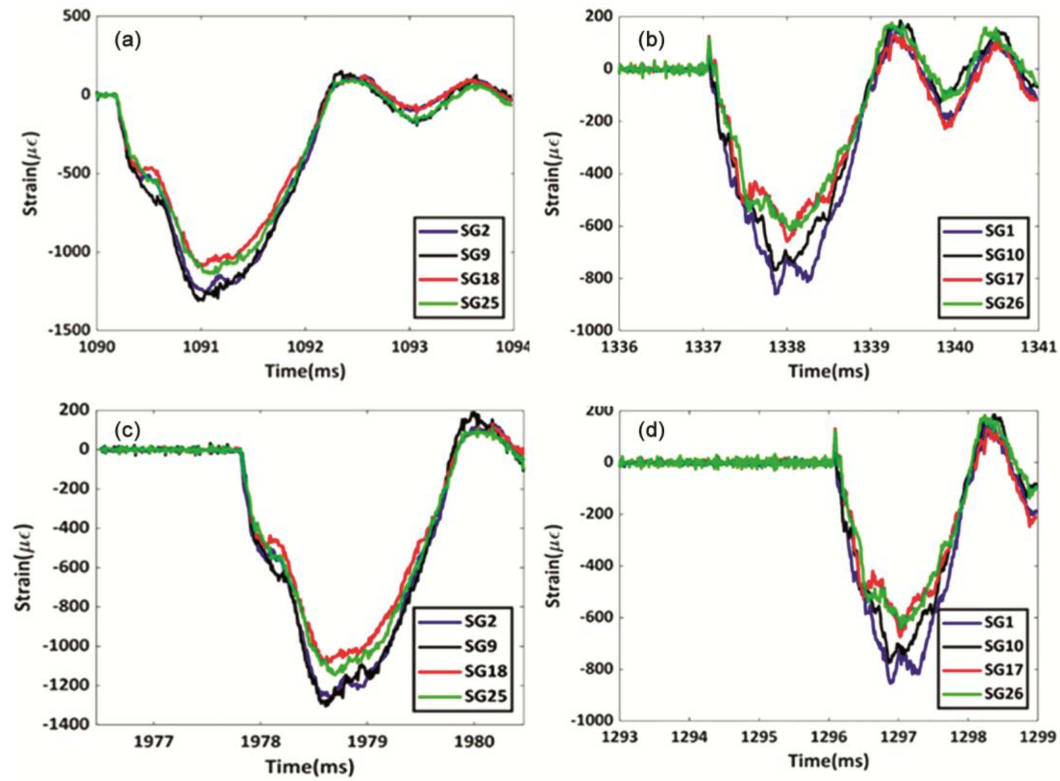


Fig. 3 — a) Strain response from SG2, SG9, SG18 and SG25 for trial 1 (10J); b) Strain response from SG1, SG10, SG19 and SG26 for Trial 1(10J); c) Strain response from SG2, SG9, SG18 and SG25 for Trial 2(10J) & d) Strain response from SG1, SG10, SG19 and SG26 for Trial 2(10J)

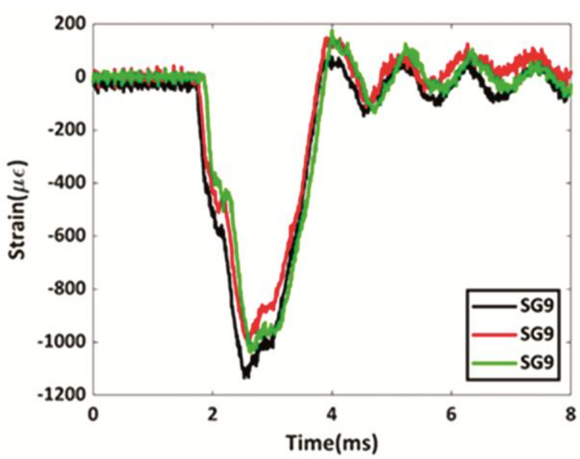


Fig. 4 — Response of transversely placed sensors for 5J impact

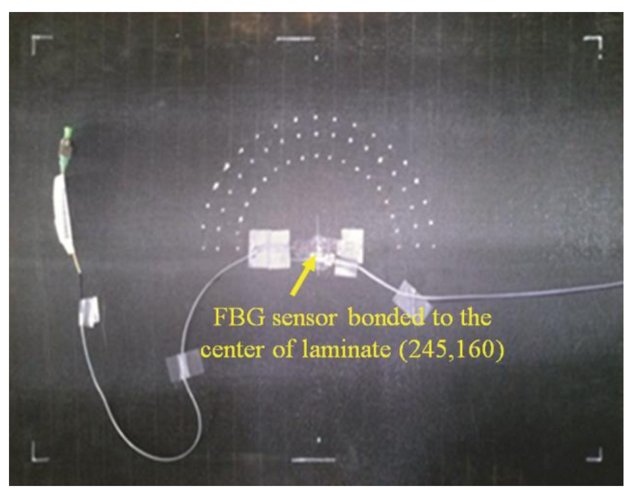


Fig. 5 — FBG sensor bonded to the center of laminate (245,160) under test

different sizes. Composite laminates of size 540mm x 370mm x 2.50mm were surface bonded on both sides with FBG and RSG at the center (245, 160) as shown in Fig. 5.

This laminate was impacted with energies 1 J and 2 J from 0° to 180° with 100 steps in a semicircle of radius 80 mm. The strain response of the FBG's and RSG's on both sides of the laminates were recorded. The normalized strain with azimuth for the top (same side of impact) and bottom (other side of impact) sensors are presented in Fig. 6(a-b). Studies were repeated on laminates of dimension 540x370x2.25 mm^3 as in previous test. In this study the strain response towards impact on semicircles of radius 70, 85 and 100 mm were carried out.

The variation of normalized strain with azimuth for the FBG and RSG are presented in Fig. 7(a-b).

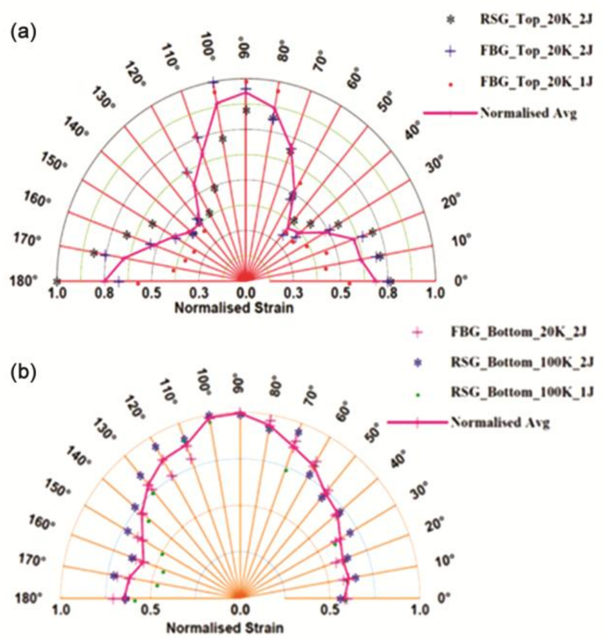


Fig. 6 — Normalized strain vs. azimuth for sensors (a) Sensor response at top of the laminate (b) Sensor response at bottom of the laminate

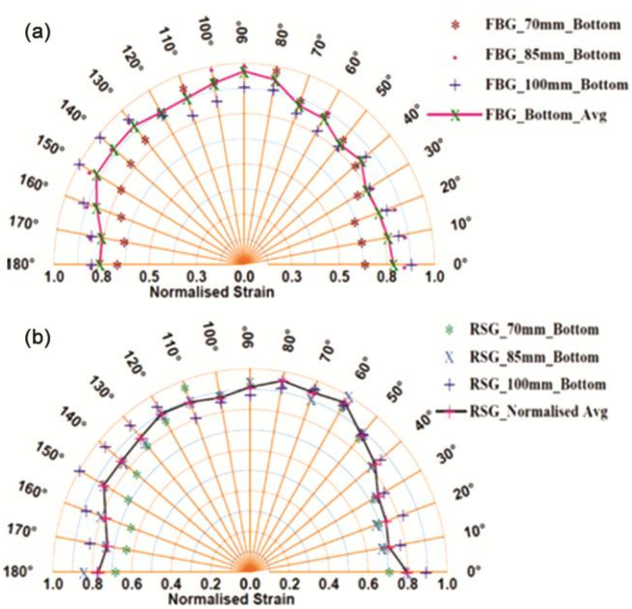


Fig. 7 — Normalized strain vs. azimuth for sensors(a) Sensor response of FBG(b) Sensor response of RSG

One can understand from the angular response of the FBG and RSG which were surface bonded on the composite laminate have similar response for impact. Studies were also carried out with strain rosette (0°-90°) on 540mm x 370mm x 2.50mm composite laminate with impacts of 2J from 0^0 to 360^0. The results are shown in the Fig. 8.

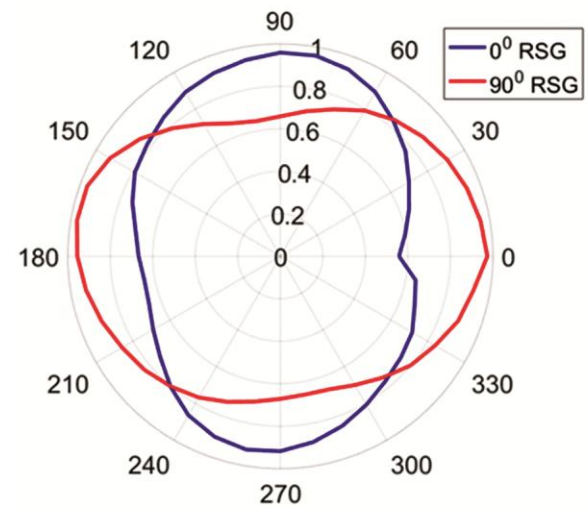


Fig. 8 — Normalized strain vs. azimuth for 0° and 90° strain rosette; the Blue line represents 0° strain gauge and Green line represents 90° strain gauge

4 Sensor network design for impact location estimation

From the studies above it is 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°. FBG and RSG responses are in agreement and repeatable over different energies. A study is carried out to see the effect of the sensor orientation in detecting the impact location which uses the strain amplitude response[24]. The amplitude-based algorithm discussed[24] is based on the fact that the maximum strain amplitude increases when an impact is located closer to a sensor. This algorithm only requires the relative position of each FBG sensor and the peak strains recorded by them. The strain Amplitude-based algorithm calculates the impact location based on the following formulation.

"The maximum strain observed during an impact for each sensor is extracted from the data, and the strain ratio between each sensor pair is computed as expressed by the following equation

$$\left[X_{impact}, Y_{impact}\right] = \left[\frac{\sum_{k=1}^{m}(Iij)x}{m}, \frac{\sum_{k=1}^{m}(Iij)y}{m}\right] \qquad \dots (3)$$

where $(Iij)x$, $(Iij)y$ *are given by:*

$(Iij)x = Xi + rij*dij*\cos\theta ij$ *and*

$(Iij)y = Yi + rij*dij*\sin\theta ij$

For increasing the accuracy algorithm[24] proposes a parameter α, which in turn selects the number of strain responses to be used in the process defined by:

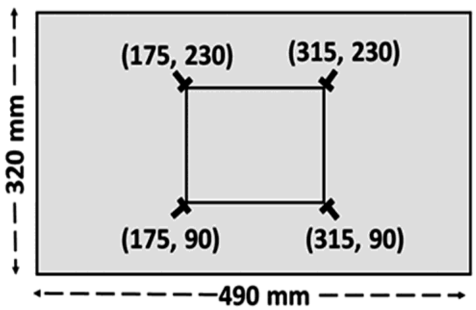


Fig. 9 — Sensor network on the 540 x 370 x 2.5mm laminate

$$\sum_{k=1}^{m} Mk \geq \alpha \sum_{k=1}^{n} Mk \quad \text{... (4)}$$

Where n is the total number of relative location points, and α is a tuning parameter which depends on both the number of sensors and also the geometry (curvature) of the given structure. Proper selection of α value results in a good estimation of impact location[24]

As part of the study, this algorithm was selected to validate the effect of the sensor network in the location estimation accuracy. Studies were carried out in composite laminate of size 490x320x2.4 mm^3 thick laminate with four RSG rosette (0-90^o) forming a grid of 70x70mm, as shown in Fig. 9. The error (Euclidian distance) in estimation is calculated as follows:

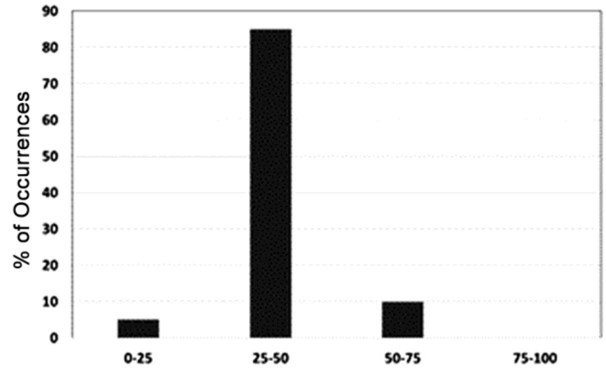
$$R = \sqrt{\left(x_{ai} - x_{pi}\right)^2 + \left(y_{ai} - y_{pi}\right)^2} \quad \text{... (5)}$$

(X_{ai}, Y_{ai}) is the actual impact location and (X_{pi}, Y_{pi}) is the impact location as determined by the algorithm.

Impact location estimations were carried out using sensors oriented diagonally and sensors oriented at 45^o using the algorithm[24]. It is observed that estimation gives superior performance when α, the tuning parameter, set to be a variable parameter. Nevertheless, when impac occur at any random location, it is needed to automate the selection of α- value to give better estimation. In this study, the alpha value is used as that value of α as a mean of normalized absolute maximum strain. It is found that this choice was able to give consistent estimation for different locations on the same structure.

Comparison of the estimation results are shown in Fig. 10(a) for the Sensors 1,2,3,4 and (b) for the sensors 5,6,7,8

It can be noticed that estimation by sensors 5, 6, 7 and 8 (which are oriented at 45° as per the sensor sensitivity studies) leads to better estimation, as the 70% of the estimation results in 0 to 25 mm error range, thus validating the sensor net design



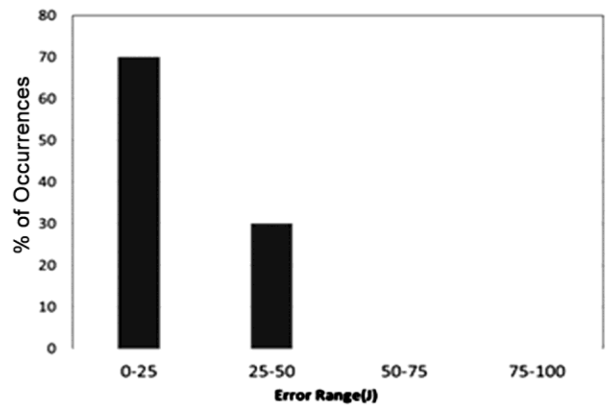


Fig. 10(a) — Percentage of occurrence of errors with sensors # 1,2,3,4 (b) Percentage of occurrence of errors with sensors with Sensors # 5,6,7,8

5 Strain scan based algorithm

Strain Amplitude based algorithm considers only the peak strain value in the estimation of the impact location. The consistency of the estimation is affected by the fact that single point used in the estimation is affected by the presence of the noise. The reliability of the estimation can be improved by incorporating more number of points in the estimation. A new approach, which considers a set of strain values around the peak value instead of a single value in strain amplitude approach. In this strain scan based method, all the values which are up to 70% of the maximum strain value are considered for calculating the impact locations. The average of these locations is then taken as the final estimated impact location validation of strain scan algorithm is carried out using the 66 impacts carried out on the impact described in the above section. The estimation result summary in comparison with amplitude based algorithm is presented in Fig. 11.

It can be observed from Fig. 11 that approx. 78% of the test results lie in the error range of up to 50 mm. Strain Scan algorithm gives reliable estimation compared to Strain Amplitude algorithm.

6 Validation using high energy impact

The performance of the algorithm was studied though high energy impacts (varying from 5J to 35J), which created BVID and VID on the laminates. Impact tests were carried out on six laminates of thickness 2.4 mm and six laminates of thickness 3.6 mm of size 560x440x2.4 mm^3. The FBG & RSG sensor grid were used for the impact location estimation (Linear Strain Gauges at S22, S12, S42, S32 and FBGs at F1, F2, F3, F4 as shown in Fig. 12).

Measured data have been processed for impact location using strain scan based algorithm all over the area covered by the sensors. The location estimations are carried out using scan based algorithms and the results are shown in Fig. 13 shows estimations carried out using FBG or RSG data on 2.4 mm thick laminates. The circle without solid edges represents actual impact and with solid edge estimated impact location and the line joining them is the representative of the error of estimation.

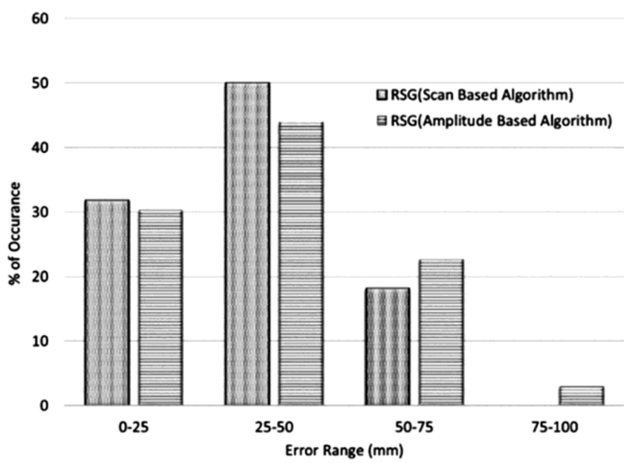


Fig. 11 — Estimation Summary using Strain scan and Strain amplitude algorithm

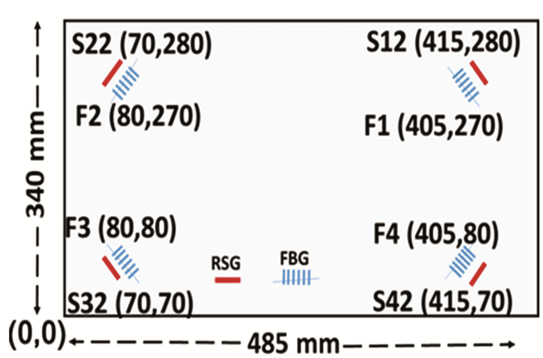


Fig. 12 — 560mm x 440mm laminate and Sensor location under test

Studies were also carried out on 3.6 mm thick laminate as above and the results are shown in Fig. 14.

It can be seen from Fig. 13 and 14 the error line for the impact outside the active zone (shaded region which the intersection of the active regions of each sensor) is higher (worst being the 50mm to 76 mm) wherein within the active zone the error in location estimation is less (best being the 8mm). Impact happening near to the sensors also results in estimations with less error. The summary of the estimations (close to 25 impacts over different laminates) in terms of error range and % of occurrence for the 2.4 mm thick laminate and 3.6 mm thick laminate is represented in Fig. 15(a-b).

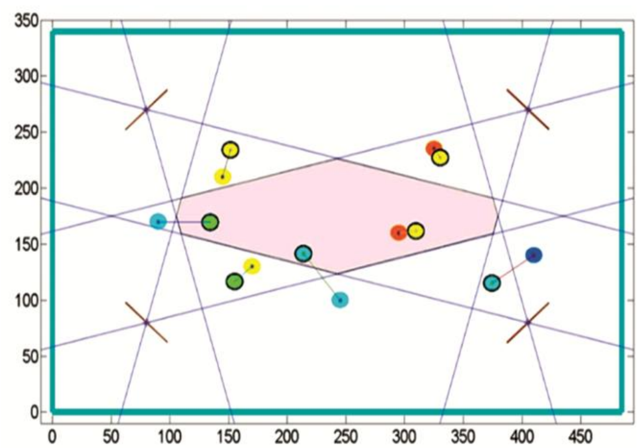


Fig. 13 — Location estimation results with FBG data on 2.4mm thick laminates

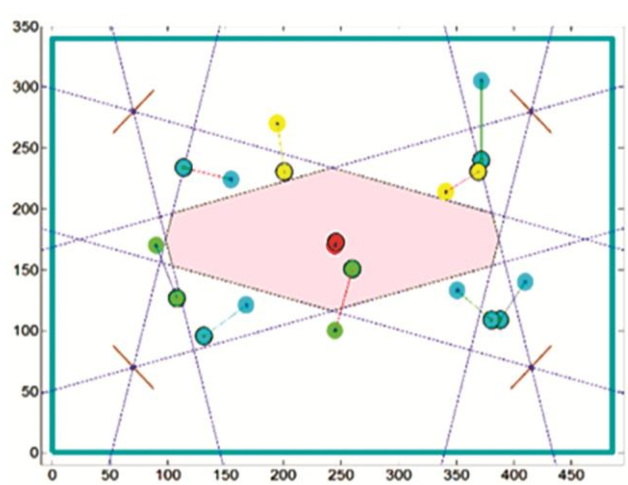


Fig. 14 — Location estimation results with RSG data on 3.6mm laminates

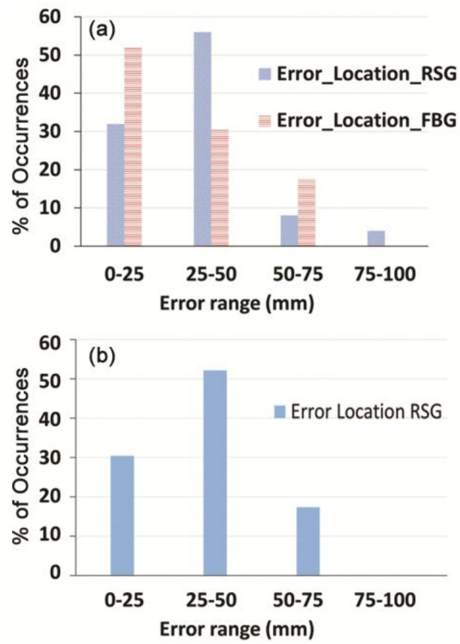


Fig. 15 — comparison of error plot: (a) 2.4 mm RSG and FBG (b) 3.6 mm RSG

7 Conclusions

We have studied strain response (angular/spatial) from FBG sensor & RSG sensors bonded to the composite structure due to the LVI. As the part of the study angular and spatial response of RSG and FBG are studied on flat laminate level. The studies showed that the sensors respond with almost the same strain for a certain angle range. Based on such experimental results, a sensor network was designed to detect the LVI. A location estimation algorithm based on the peak strain experienced by the sensor bonded to the structure was used to verify the location estimation capabilities of the sensor network. The studies showed that FBG or RSG oriented at 45° on the four corners in a laminate can cover the maximum area, and can result in better estimations compared with another orientation using the same algorithm. Further, we have improved the performance of the algorithm by using weighted average of the strain instead of peak amplitude. Here we found the α (tuning parameter) which is mean value of normalized absolute maximum strain across the sensors provides the better estimation for different LVI location.

The studies also suggested FBG gives superior results compared to RSG due to its superior noise rejection capability. The algorithm has been verified using high energy (35 J)with maximum estimation error of 50 mm for 80% trial case. We found that majority of high error (>50 mm)was observed for regions outside the active zones. Furthermore, we are going to report on development of algorithm and relative performance on estimation for LVI localization in later publications.

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