Title

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Impact Detection and Localization in Composite Material Systems with Embedded Fiber Bragg Gratings

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Abstract

Composite material systems are increasingly being used in numerous structural applications due to their weight, corrosion resistance, and thermal/acoustic properties. Fiber Bragg grating (FBG) optical sensing arrays may be used in the implementation of a structural health monitoring (SHM) approach for in-situ assessment of the integrity of such material systems, and they may be embedded directly into the composite structure during fabrication, allowing for integrated, internal sensing of strain/load states. In this paper, a 1.22 m x 1.22 m in x 1.2 cm fiberglass composite panel was fabricated with 40 embedded FBGs and subjected to an extensive test matrix of various impact force levels at different locations. Impacts were delivered via a customized pendulum impact hammer system, which could deliver impact velocities up to approximately 5 m/s. The detection and localization problems were approached via features extracted from autoregressive models trained on the FBG network response as well as power spectral density estimates of measured response; these features were used in a multi-variate predictor from which Mahalanobis distance measures were used for the detection (and exploration of the classification, e.g., delamination size) problems. Results showed excellent characterization of the impacts and subsequent delamination zones under statistical hypothesis testing.

Keywords: Fiber Bragg gratings, impact detection, impact localization, embedded arrays, composite materials

1. INTRODUCTION AND EXPERIMENTAL SETUP

Structural Health Monitoring (SHM) is the implementation of a damage assessment strategy to reduce operational costs and/or life safety risks[1]. The SHM of composites is a rapidly growing research area as composite material systems are gaining prevalence in many structural applications[2] for a variety of performance advantages; however, these are challenged by a less-than-robust understanding of material failure and the general absence of visual damage cues. This work simulates an impact-induced damage detection scenario with a representative composite specimen using embedded FBG sensors as the in-situ sensing methodology.

The experimental test specimen is a 1.22m x 1.22m x 1.2cm woven fiberglass prepreg panel with FBG sensors embedded under the top ply. Figure 1 (left) presents the design schematic of the panel along with its final installation in the test fixture. The schematic shows the layout of the 40 embedded sensors serialized within 4 optical arrays with 10 sensors per array. The schematic also shows the designed routing of excess optical fiber between sensors. The extruded aluminum test fixture includes an impact pendulum with a load cell for measuring impact force, and a laser photo-interrupter system to measure velocity of the pendulum head at impact. A fully clamped boundary condition was used for the experiment.

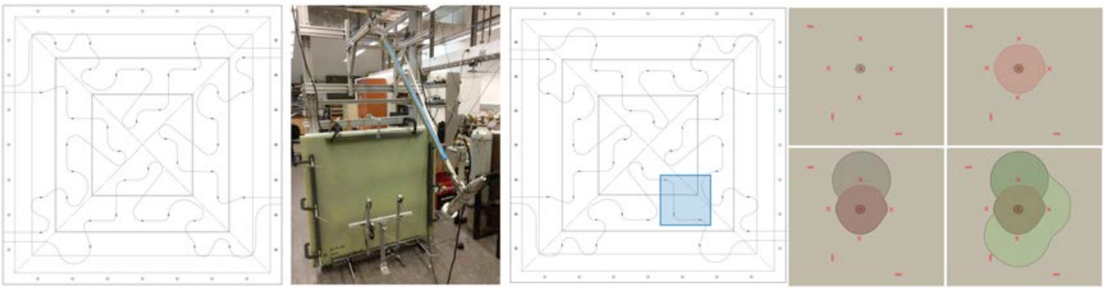

Fig. 1. Sensor layout and installation in test fixture of the test article (left); delamination areas: top left (1.86 cm^2), top right (55.5 cm^2), bottom left (111.4 cm^2), and bottom right (208.5 cm^2) (right).

Impact damage in the form of delamination was introduced through repeated impacts of the panel with the impact head. The dynamic strain response of the panel to a pseudorandom loading generated by an affixed electromechanical shaker was recorded for 2 minutes between damage states. Figure 1 (right) depicts the damage progression within the panel.

2. DAMAGE DETECTION AND LOCALIZATION

For this study, damage sensitive features in both the frequency and time domain are explored. The observation that damage-induced changes in the structural properties of a system will produce changes in vibration frequency is the underlying assumption motivating the exploration of frequency domain features[3]. The multivariate feature vector will be the change is vibration frequency among all peaks in the power spectral density estimate given by equation (1)

$$\mathbf{x} = \arg\max\left(\hat{S}_{xx}^{u}\left(\omega_{j}^{u}\right)\right) - \arg\max\left(\hat{S}_{xx}^{bl}\left(\omega_{j}^{bl}\right)\right), \tag{1}$$

where $\hat{S}_{xx}^{bl}$ and $\hat{S}_{xx}^{u}$ are the power spectral density estimates for the baseline and unknown structural states respectively, and j is the peak number index. In the time domain, the coefficients, a_i, of an autoregressive model given by

$$x(n) = \sum_{i=1}^{p} a_i x(n-i) + e(n), \tag{2}$$

are used as the damage sensitive feature[4]. In both cases, the multivariate feature vectors must be mapped to a scalar metric to perform the outlier discrimination analysis, so the Mahalanobis squared distance

$$D_i = \left(\mathbf{x}_i - \overline{\mathbf{x}}\right)\Sigma^{-1}\left(\mathbf{x}_i - \overline{\mathbf{x}}\right)^T \tag{3}$$

is employed as a covariance-weighted distance measure. Representative test results are given in Figure 2 for both the frequency and time domain.

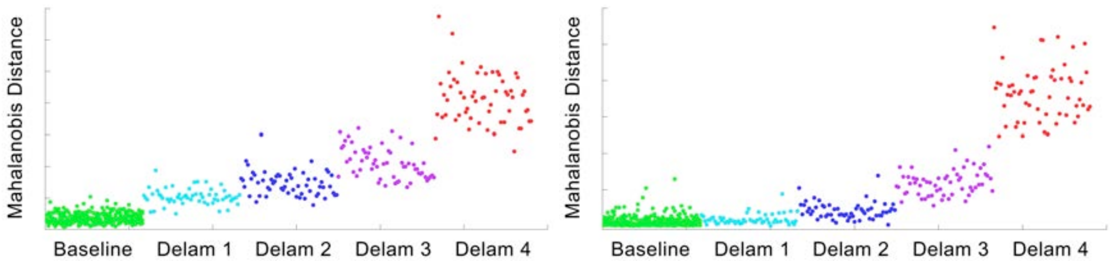

Fig. 2. Malanobis distance measurements for frequency domain feature, sensor 17 (left) and time domain feature, sensor 24 (right)

The correlation between Mahalanobis distance and delamination size provides promise for damage detection via statistical hypothesis testing. To localize the damage, the unobservable random error, $e(n)$, from the auto regressive model in (2) is used. For all possible sensor pairs, the AR coefficients from the first sensor in the pair are used to predict the other sensor and the prediction error is calculated for both the baseline and the damaged cases. The ratio of these prediction errors is the damage sensitive feature given in equation (4).

$$\delta_p = \frac{RMS\left[e_{p,\,damaged}(n)\right]}{RMS\left[e_{p,\,baseline}(n)\right]}, \tag{4}$$

The underlying assumption is that the performance of the prediction should be relatively unchanged if both sensors are far removed from the damage. If one of the sensors in the pair is

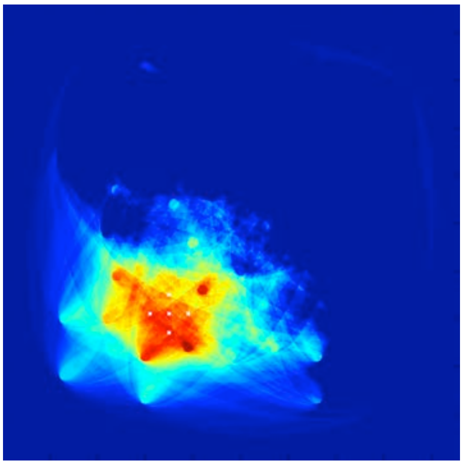
Figure 3. Delamination imaging.

close to the damage, local dynamic anomalies will degrade the performance of the AR model and push the ratio higher than unity. Imaging of the localized damage can be performed according to,

$$I_{damaged}\left[i,j\right]=\sum_{i=1}^{p}\delta_p M_p^{\theta} - \sum_{i=1}^{p} M_p^{\theta} , \quad (5)$$

where M^{θ} is an elliptical image mask where the foci are the two sensors in a given sensor pair, *i* and *j* are the pixel indices, *p* is the number of pairs, and δ_p is the feature from (4). The implementation of the imaging is shown in Figure 3 for the 208.5 cm^2 delamination.

3. CONCLUSIONS

In this work, damage detection and localization schemes were implemented on a large composite panel with an array of 40 embedded FBG strain sensors. Using Mahalanobis distances from multivariate time and frequency domain features, a strong correlation between delamination size and Mahalanobis distance was observed. Initial damage localization was also performed using cross-sensor prediction of AR models.

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