

**DELAMINATION DETECTION AND GROWTH ASSESSMENT IN
COMPOSITE LAMINATED BEAMS USING A DATA-DRIVEN
VIBRATION STRUCTURAL HEALTH MONITORING
METHODOLOGY**

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This study presents an integrated and reliable Structural Health Monitoring (SHM) methodology for composite laminated structures that enables delamination assessment. Most of these structures are subjected to vibrations and therefore, vibration-based SHM (VSHM) methods present an attractive possibility. The vibration response is used as an input in the data-driven VSHM methodology to estimate, based on the output of statistical models, the development of delamination's behaviour. This study presents a technique based on Singular Spectrum Analysis (SSA) for a data-driven VSHM methodology. The methodology decomposes the vibration responses in a certain number of principal components where the data is better distinguishable. The methodology has been implemented on the vibration responses measured by embedded piezoceramic sensors in an experiment with four composite laminated beams. The size of the delamination has been modified to study its growth. The results demonstrate a substantial potential of this approach for delamination detection and growth assessment.

INTRODUCTION

Composite materials are continuously gaining more importance and their applications are constantly growing as a result of their advantageous properties, most notably their large strength-to-weight ratio, corrosion resistance, high impact strength and their magnificent design flexibility. They are steadily replacing traditional structures in a wide range of industry sectors, including the aerospace, wind energy, marine, and oil and gas industries and even in every day structures such as oil and gas pipelines, structural parts in compressors and turbines, aircraft structures (e.g. A350 with more than 53% made of composites) and structural parts in wind and marine turbines (1).

They are in structures designed to last long and they must be designed to withstand deterioration for a certain lifetime with a maximum of performance. To guarantee the best of their performance, data-driven VSHM methodologies provide the maximum control for damage assessment as well as clearly demonstrate safety and reliability efficiency in terms

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of structure life cycles by reducing the downtime due to maintenance. Delamination is one of the most common damages in these structures and it does not follow conventional patterns but it exhibits complex failure modes which are difficult to identify by visual or conventional techniques (2).

The method proposed in this study is based on a technique known as a Singular Spectrum Analysis (SSA) that it is a natural extension of Principal Component Analysis (PCA) for non-independent data such as time series (3). It has been implemented as VSHM technique in several studies for damage assessment (4, 5). The methodology for delamination detection is a non-parametric technique which is able to decompose the vibration responses, discretised into signal vectors, in certain number of principal components taking into account all the rotational patterns at each frequency. Based on the principal components, a reference state is created where the observation signal vectors can be compared to obtain sensitive features for delamination assessment. The sensitive features are projected onto the feature space where a damage index is obtained to assess delamination.

This paper is organised as follows, first the suggested data-driven methodology is introduced. The methodology is then applied as a delamination assessment methodology for vibration responses measured by embedded piezoceramic sensors in the composite laminated beams with and without delamination. The experiment set up and the manufacturing process of composite laminated beams is described as well as the procedure for data collection. The paper concludes with the delamination assessment discussion and conclusions.

DELAMINATION ASSESSMENT METHODOLOGY

The methodology is considered as a simple, nonparametric method for data compression and information extraction. The procedure is divided in four steps: data collection, creation of the reference state, feature extraction and delamination assessment.

Data collection

The first step is to collect the data from the composite laminated beams in consideration. The voltage signals were measured from the embedded piezoceramic sensors in the composite laminated beams. Each signal $\mathbf{x} = (x_1, x_2, \dots, x_N)$ was discretised into a vector with dimension N. Each signal was normalised to have zero mean and unity variance (6). The signal vectors for each realisation were arranged in columns into the matrix \mathbf{X} with a dimension $N \times M$ where M is the number of realisations considered.

$$\mathbf{X} = (\mathbf{x}_1, \mathbf{x}_2, \dots, \mathbf{x}_m, \dots, \mathbf{x}_M) \quad (1)$$

Creation of the Reference State

The methodology creates a reference state based on the reference composite laminated beam which is considered as a healthy beam without any delamination (see section of experiment set up). The observation signal vectors recorded from the different composite laminated beams with and without delamination can be compared with the reference state.

Embedding

An embedding matrix is created for considering more dimensions from a single signal vector and thus more features, contained in the signal vector, are uncovered.

Each signal vector \mathbf{x}_m is embedded into a matrix $\tilde{\mathbf{X}}_m$ by W-lagged copies of itself as shown in Equation 2 where $m=1,\dots,M$ and W are the number of signal vector realisations and the sliding window size, respectively. The dimension of the matrix $\tilde{\mathbf{X}}_m$ is $N \times W$.

$$\tilde{\mathbf{X}}_m = \begin{pmatrix} x_{1,m} & x_{2,m} & x_{3,m} & \dots & x_{W,m} \\ x_{2,m} & x_{3,m} & x_{4,m} & \dots & x_{(W+1),m} \\ x_{3,m} & x_{4,m} & x_{5,m} & \dots & \vdots \\ x_{4,m} & x_{5,m} & \vdots & \dots & \vdots \\ x_{5,m} & \vdots & \vdots & \dots & x_{N,m} \\ \vdots & \vdots & x_{(N-1),m} & \dots & 0 \\ \vdots & x_{(N-1),m} & x_{N,m} & \dots & 0 \\ x_{(N-1),m} & x_{N,m} & 0 & \dots & 0 \\ x_{N,m} & 0 & 0 & \dots & 0 \end{pmatrix} \quad (2)$$

Each $\tilde{\mathbf{X}}_m$ matrix is included in a larger matrix $\tilde{\mathbf{X}}$ with dimension $N \times (MW)$ as shown in Equation 3. The number of signal vector realisations is normally selected as $M \leq W$.

$$\tilde{\mathbf{X}} = (\tilde{\mathbf{X}}_1, \tilde{\mathbf{X}}_2, \dots, \tilde{\mathbf{X}}_m, \dots, \tilde{\mathbf{X}}_M) \quad (3)$$

Decomposition

The embedded matrix $\tilde{\mathbf{X}}$ is decomposed into a number of vector components based on their variance content. The covariance matrix of $\tilde{\mathbf{X}}$ is calculated as detailed in Equation 4, where $\tilde{\mathbf{X}}^t$ is the transpose matrix of $\tilde{\mathbf{X}}$.

$$\mathbf{C}_X = \frac{\tilde{\mathbf{X}}^t \tilde{\mathbf{X}}}{N} \quad (4)$$

The eigen-decomposition of \mathbf{C}_X yields to the eigenvalues storage into the diagonal matrix $\mathbf{\Lambda}_X$ in decreasing order and the eigenvectors stored in columns into the matrix \mathbf{E}_X in the same order than their corresponding eigenvalues. \mathbf{E}_X^t is the transpose matrix of \mathbf{E}_X .

$$\mathbf{E}_X^t \mathbf{C}_X \mathbf{E}_X = \mathbf{\Lambda}_X \quad (5)$$

The Principal Components (PCs) A_k associated with each eigenvector contained in E_X are calculated by projecting \tilde{X} onto E_X as shown in Equation 6 for $n=1\dots N$.

$$A_n^k = \sum_{w=1}^W \sum_{m=1}^M X_{m,n+w} E_{m,w}^k \quad (6)$$

Reconstruction of the reference state

The Reconstructed Components (RCs) are obtained by convolving the PCs with the associated eigenvector, thus the k^{th} RC ($k \leq MW$) at n -value ($n=1\dots N$) for each m -realisation is given by Equation 7.

$$R_{m,n}^k = \frac{1}{W_n} \sum_{w=1}^W A_{n-w}^k E_{m,w}^k \quad (7)$$

Each $R_{m,n}^k$ value is normalised by the normalization factor as shown in Equation 8.

$$W_n = \begin{cases} n & 1 \leq n \leq W - 1 \\ W & W \leq n \leq N \end{cases} \quad (8)$$

The RCs are then arranged as columns into the matrix $\mathbf{R} = (\mathbf{R}^1, \mathbf{R}^2, \dots, \mathbf{R}^m, \dots, \mathbf{R}^M)$ with a dimension $N \times MW$. Each of the M -signal vector realisations are decomposed into W -reconstructed components arranged into columns in the matrix \mathbf{R}^m and it defines the reference state of the healthy composite laminated beam without any delamination where the new observations can be compared.

Feature extraction

The feature vectors (FVs) of each observation signal vector are obtained by multiplying each observation signal vector \mathbf{x} by the reference state \mathbf{R}^m as shown in Equation 9 where $j=1,\dots,W$.

$$T_j = \sum_{n=1}^N x_n R_{n,j}^m \quad (9)$$

Each T_j value is arranged into a vector \mathbf{T} with dimension W and it is considered as the FV of each observation signal vector onto the reference state.

Delamination assessment

Delamination is assessed by comparing the observation FVs in the feature space and measuring its distance to the baseline feature matrix \mathbf{T}_B by the Mahalanobis distance (7).

T_B is calculated by the observation FVs corresponding to the reference composite laminated beam without any delamination. The dimension considered in this analysis was $p = 3$ where ($p \leq W$), in this sense only the first three FVs were used for the delamination assessment. The similarity of each observation feature vector T with the baseline feature matrix T_B was used as a delamination index D . In order to label an observation as an outlier (delaminated beam) or inlier (non-delaminated beam), there is a need to set a threshold against each observation delamination index D can be evaluated. The threshold is calculated based on the mean of distances measured by baseline feature vectors to the baseline feature matrix plus two times their standard deviation. Therefore, the classification of a new FV is based on the comparison of its damage index D to the defined threshold.

$$\begin{aligned} \text{Non-delaminated beam} \quad & \mathbf{H1}: D \leq \text{Threshold} \\ \text{Delaminated beam} \quad & \mathbf{H2}: D > \text{Threshold} \end{aligned} \quad (9)$$

EXPERIMENT SET UP

Material and manufacturing process of the composite laminated beams

Four laminated beams were manufactured by hand lay-up and reinforced using weave fabric woven PP-25 carbon fibres impregnated with thermosetting epoxy resin system from ACP Composites. A total of 10 layers were used to produce 2.5 mm thickness of the beam. The beams were placed into a vacuum bag for the process of curing inside the autoclave and compressed by steel plates. The parameters of the curing recipe were selected as follows: The air temperature was incremented at 3°C/min and posterior hold at 154°C for one hour. The pressure in the vacuum bag was set at 1.4 bar. After an hour at 154°C the temperature slowly decreased up to 66 °C before removal of pressure. The final dimensions of the beams were 310 x 45 x 2.5 mm.

Three of the four beams were designed to have different delamination sizes as detailed in Table 1 and Figure 1. The delamination was introduced during the manufacturing process. A Teflon sheet was introduced, with the dimensions and locations detailed in Table 1, before the manufacturing process as shown in Figure 2a. The non-adherent property of the Teflon sheet defines a region where the connection between the laminates, in both upper and lower sides, does not bond.

Two piezoceramic (PZT) sensors model PSI-5A4E with diameter 12.7mm and thickness 0.191 mm from Piezo Systems INC were embedded within the 3th layer. A circular cut was made in the 3th layer and two stripes of copper were first isolated and then extended until the short edge of the beam. One of the copper stripes was extended along the top surface of the layer 3th and the other along the bottom surface as shown in Figure 2c. In this case both poles of the PZT were isolated. The copper stripes were used as permanent electrodes and then connected by wires to the DAQ NI-USB-6009 as shown in Figure 2b.

TABLE 1 – Delamination scenarios

Beam	Location		Size	
	Lengthwise	Layers	Length (mm)	Width (mm)
B1	non-delaminated			
B2	Middle of beam length	5 th – 6 th	40	45
B3	Middle of beam length	5 th – 6 th	80	45
B4	Middle of beam length	5 th – 6 th	100	45

Test rig for data collection

A test rig was installed to minimise the effect of the boundary conditions when measuring the vibration response of the composite laminated beams. The beams were supported in a frame with fishing lines as shown in Figure 3. This set up allows changing the beam without introducing serious changes on of the boundary conditions. Once a beam is on the test rig, it was excited by a sharp impact introduced with a hammer in the middle of the span. A set of free-decay vibration signals was recorded by a DAQ NI-USB-6009. The procedure was repeated to obtain 20 signals for each beam scenario.

DELAMINATION ASSESSMENT RESULTS

The data collected consisted on voltage vibration responses from all different composite beams configurations as detailed in Table 1. A total of 80 signal vectors (20 for each beam) were obtained from the vibration responses measured at sampling frequency of 1000Hz. Each vibration response was discretised into a vector with length $N = 2048$. A Fourier transform was applied to each signal vector to obtain its corresponding frequency spectrum with now a dimension $N = N' = N/2 = 1024$. The reference state was constructed with $M = 5$ signal vectors on the non-delaminated beam B1. The sliding window size was selected as $W = 10$. A comparison of the reconstructed spectrum line of the B1 by using only the first three RCs (RC₁, RC₂ and RC₃) and the original frequency spectrum of B1 can be seen in Figure 4. It is clearly observed that the reconstructed spectrum draws with a smooth spectral line the general trend of the original one.

The FVs were calculated by the inner product between each observation signal vector and the reference state as defined in Equation 9. In order to visualise the performance of the FVs onto the feature space, all FVs were projected onto a two dimensional space as shown in Figure 5a. It can be observed that different clusters were formed with clear distinction between B1 (non-delaminated) and B2, B3 and B4 (delaminated ones). The cluster points between B2 and B3 are mixed and confused however the cluster points corresponding to B4

are clearly distinguishable not only from B1 but also from B2 and B3. This demonstrates that small delamination sizes are more difficult to be identified. In order to evaluate the effect of delamination detection but also its growth, the dimension of the FVs was extended to three. The delamination index values are represented in the Figure 5b where all 80 observation signal vectors are compress to a single value. It is observed that most of the delamination index values corresponding to any of the delaminated composite beams are above the threshold line meanwhile the delamination index values corresponding to the non-delaminated composite beam are below the threshold line. Therefore, the results show that the data-driven methodology is able to distinguish between delaminated and non-delaminated beams. Moreover, it can be observed that when the length of the delamination increases, it is represented with a larger delamination index value. In this sense the methodology is not only able to detect delamination sizes of 40 mm (approximated 13% of the length of the beam) but also it is able to track its growth.

CONCLUSIONS

This paper presents a study that uses a data-driven VSHM methodology for detecting and growth tracking of delamination in carbon fibre laminated beams with embedded PZT sensors between the laminates. The methodology takes into consideration the inter-correlations between the variables contained in an individual signal vector obtained in the vibration response of the beams. Based on a reference state created by the reconstruction of spectral lines on the non-delaminated beam, feature vectors are obtained that contains sensitive information about the presence and extend of the delamination. The results of this study demonstrate that the effect of delamination introduces alterations in the vibration response of the composite laminated beams. This effect can be successfully observed in delamination index values used to detect delamination based on a reference state. The delamination was successfully detected but also an increment in its length was tracked. Overall, the data-driven VSHM methodology presented in this study is proven to give adequate information about the present and extend of delamination.

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FIGURES

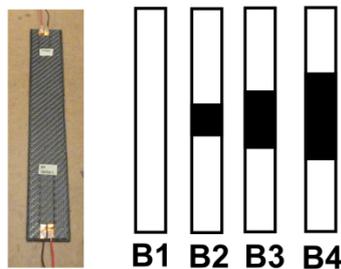


FIGURE: 1 - Composite laminated beams delamination configuration

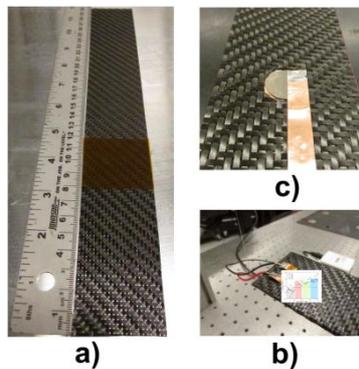


FIGURE: 2 – a) Delamination introduced by a Teflon sheet. b) PZT sensor location. c) Electrodes.

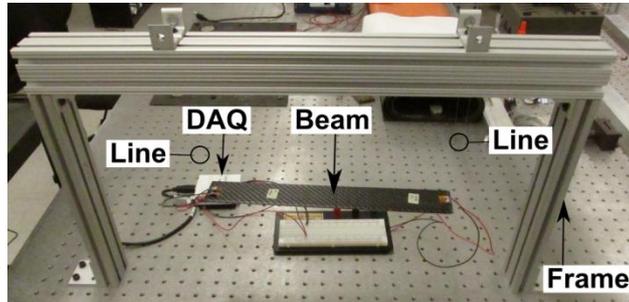


FIGURE: 3 – Test rig set up

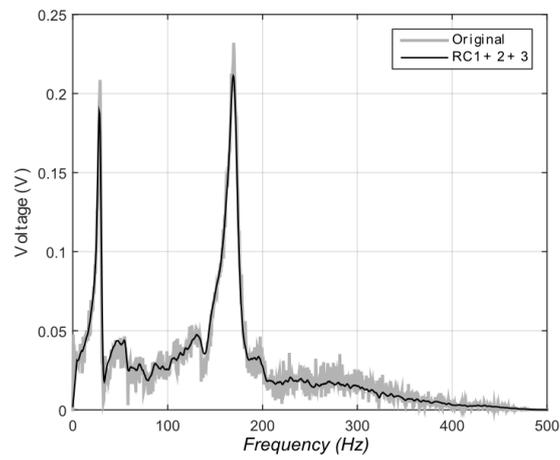


FIGURE: 4 – Reconstructed frequency spectrum with the first three RCs ($RC_1 - RC_2 - RC_3$)

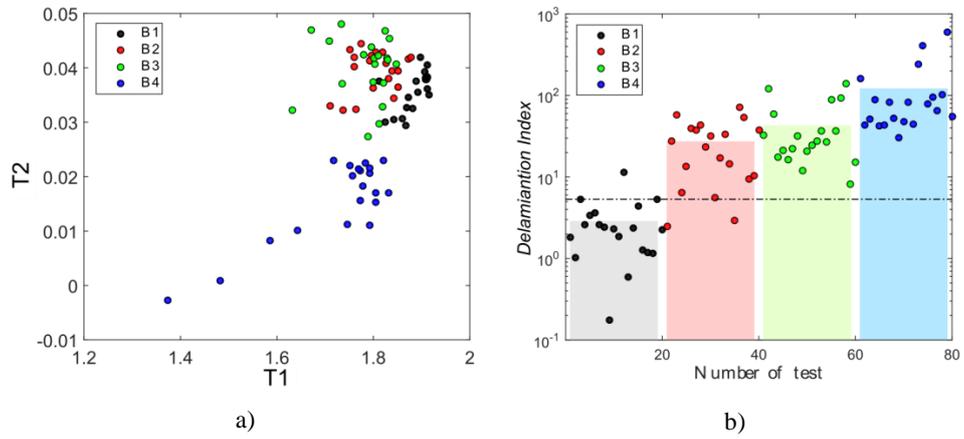


FIGURE: 5 – Cluster and delamination detection index plots for the four composite laminated beams.
a) Cluster effect onto 2-D space defined by $T_1 - T_2$ b) Damage index using a three dimension FV ($T_1 - T_2$ and T_3).