# VIBRATION-BASED DELAMINATION DETECTION IN COMPOSITE BEAMS BASED ON NONLINEAR SIGNAL ANALYSIS

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## Abstract.

*This study addresses the question for delamination detection in composite laminate beams. A vibration-based approach towards the problem is adopted. This work proposes a novel concept for delamination monitoring in composites based on a nonlinear signal correlation. Experiments are performed on undamaged and delaminated beam and their free decay response is used. The dynamic response is registered by an accelerometer in two different points to use the correlation between the two signals as a metric for delamination identification. Experiments show that the proposed method accurately detects and localizes delamination in a carbon fiber composite beam.*

## 1 Introduction

Maintenance and operation costs are usually among the largest expenditures for most structures - civil, aerospace, and military. An ageing structure may reduce profits with increased maintenance costs and down time and it can become a hazard for its users. The ability to access the integrity of a structure and discover a fault at a rather early stage, before it has developed so that it can cause damage to the structure, can significantly reduce these costs. A large class of the structural health monitoring (SHM) methods are vibration-based methods where the state of the structure is assessed using its vibration response.

A composite material is a combination of two or more materials to achieve better properties. Such kind of structures are having nowadays an increasing importance in many contemporary industrial, civil and military applications, in particular in the aviation field, and are progressively replacing traditional materials due to their well-known advantages. The greatest advantage of composite materials is the possibility to make them very strong and light at the same time, compared to traditional ones. Technology developed a large number of structures made of composites, but among them, the most important one is the laminate. Laminates are structures made of two component: fibres and resin. Fibres are often made of carbon, glass or Kevlar, while resin is commonly epoxy. Resin keeps the fibres together and give toughness to the component, while fibres carry on the loads and provide stiffness and strength. Such structures are layered structures and the ply orientation depends on the expected directions of the loads. Beside many good characteristics, composite structures present also some difficulties, particularly due to their layered nature, which induce the formation of new failure modes, respect to those of conventional materials. Delamination is probably the most common failure mechanisms for composite materials: repeated cyclic stresses, impact, deformations and so on can cause layers to separate and induce a significant loss of mechanical strength. Delamination is particularly dangerous because a composites can lose up to 60% of its stiffness and toughness, and still remain visibly unchanged.

In this work the authors focus their attention on the vibration response of composite laminate materials. Laminates are very difficult to inspected and almost impossible to repair, thus evaluation of health state of such a structure gets huge importance in industrial applications. Particular interest is focused on nondestructive techniques due to their suitability to be used on working structures in order to detect and evaluate possible damages. Non-Destructive Health Monitoring methods include the use of ultrasound [1,2], optical fibres embedded with optical time domain reflectometer [3], radiographic imagining [1,4], infrared imaging [1,5], acoustic emission monitoring [1,6,7], and vibration-based monitoring methods [2,8]. This work focuses on vibration-based structural health monitoring (VSHM). These methods use the vibration response of a structure to make conclusions about its health and damage state. From the dynamic response, some parameters (modal frequencies, mode shapes, modal damping ratio and so on) can be used to estimate the health state of the structure. The basic idea of these methods is that any changes in a structure, including damage and delamination, result in changes of its physical and mechanical properties which in turn affect its vibration response. Thus the vibration response carries information about the health and damage state of a structure. From the variation of the chosen parameter it is possible to have accurate information about the presence of damage, and sometimes about its size and location. Among the most common features are the ones extracted from the modal properties, like resonant frequencies, damping and mode shapes. All of them have their advantages and disadvantages, some of the main problems being lack of sensitivity to damage, and difficulties to estimate from measured data. Another large group of monitoring methods, the model-based methods assume and use a model for the structure under interrogation.

The use of VSHM in composites has been applied to investigate two main failure modes: matrix crack and the delamination. These methods have the advantage that they can be used on a working structure for on-line monitoring. Zou et al. [9] provided a comprehensive review of the vibration-based structural health monitoring techniques developed for characterization of delaminated composite structures. They mentioned that the occurrence of a delamination in a composite structure would decrease structure’s natural frequencies and increase its modal damping as compared to the intact structures. Adams, et al. [10] tested glass-reinforced plates to attempt to detect damage after both static and fatigue torsional loading. The main mode of failure was matrix shear cracking. They found damping changes to be more sensitive than frequency shifts for detecting the onset of damage. They also noted that some changes in dynamic properties in the early stages of damage could be recovered after a rest period. Cawley and Adams [11] apply a frequency-shift-based damage detection routine to several damage cases (holes, saw cuts, crushing with a ball bearing, local heating with a flame, and impact) in composite materials (CFRP plates and honeycomb panels with CFRP faces). They were able to locate low levels of damage accurately. Sanders, et al. [12] measured modal parameters on damaged graphite/epoxy $[0/90_3]_s$ beams. Damage was induced by tensile loading the beams to 60%, 75%, and 85% of the ultimate tensile strength. Damage was predicted using a sensitivity method and the measured frequencies. Because the measured mode shapes were of poor resolution, they were not used in the prediction. Results agreed well with independently obtained results based on static stiffness measurements and crack densities from edge replication. Because this damage was approximately uniform throughout the beam, the ability of the method to localize damage was not demonstrated. Diaz Valdes and Soutis [13] used a novel method known as resonant ultrasound spectroscopy to determine the modal frequencies of a composite beam obtained from an eight-ply [0/90/90/0]s carbon/epoxy laminate of size 330 mm x 300 mm. The laminate was fabricated using T800-924C prepreg tapes. They used commercial, brass backed, piezoceramic transducer and a piezoelectric film element (AMP Inc., LDTO-028-K) bonded near the beam's fixed end and operated as actuator and sensor respectively. Changes of the modal frequencies after delamination initiation, compared to those of a non-delaminated specimen, gave a good indication of the degree of damage, demonstrating the feasibility of using measured changes in the vibration characteristics to detect damage. Among the most common features are the ones extracted from the modal properties, like resonant frequencies, damping and mode shapes. All of them have their advantages and disadvantages, some of the main problems being lack of sensitivity to damage, and difficulties to estimate from measured data. Another large group of monitoring methods, the model-based methods assume and use a model for the structure under interrogation. Most of these methods use a linear structural model. Monitoring methods based on the time-domain vibration signatures represent a relatively new paradigm in SHM [14-16]. These methods are mostly based on non-linear dynamics tools and signal analysis and most of them utilize statistical characteristics. They represent a very attractive alternative since they do not assume any model or linearity of the structure under interrogation and they only require the measured structural vibration signals in the current and possibly in a baseline (undamaged) state. In [14] the authors of the current study make use of the resonant frequencies of a composite beam for the purposes of delamination assessment.

But it should be noted that structures made of composites on a lot of occasions demonstrate quite well expressed nonlinear behaviour. This is mainly due to their material properties and the fact that they are inhomogeneous. Traditional spectrum analysis and modal analysis are applicable to structures with linear dynamic behaviour and thus strictly speaking they cannot be applied to composites. On the other hand on a lot of occasions the measured vibration response signal from structures made of composites is a nonlinear one and thus it is difficult and on some occasions even impossible to extract any information including the natural frequencies from its frequency domain representation. Most of the above mentioned methods use a linear structural model. Monitoring methods based on the time-domain vibration signatures represent a relatively new paradigm in SHM [15-17]. These methods are mostly based on non-linear dynamics tools and signal analysis and most of them utilise statistical characteristics. They represent a very attractive alternative for composite structures since they do not assume any model or linearity and they only require the measured structural vibration signals in the current and possibly in a baseline (undamaged) state. One such damage assessment method based on a novel concept for the comparison between two signals measured on a composite beam, their cross-correlation is presented here.

## 2 The main idea of cross-correlation and its application for delamination detection

Cross-correlation is a measure of similarity of two signals as a function of a time-lag applied to one of them. Let *x(t)* and *y(t)* are two signals measured on the structure. The cross correlation between *x(t)* and *y(t)* is defined as follows [18]:

$$R_{xy}(\tau) = \lim_{T\to\infty} \frac{1}{T}\int_0^T [x(t)-\mu_x]\cdot[y(t+\tau)-\mu_y]dt \qquad (1)$$

where $\mu_x$ and $\mu_y$ are the mean values of *x(t)* and *y(t)* respectively. Or for discrete signals:

$$R_{xy}(m) = \lim_{N\to\infty} \frac{1}{N}\sum_{n=1}^{N} [x(n)-\mu_x]\cdot[y(n+m)-\mu_y] \qquad (2)$$

The cross correlation is a signal as well. It has a maximum when the two signals are aligned. The normalized cross-correlation function between two signals is defined as:

$$\rho_{xy}(m) = \frac{R_{xy}(m)}{\sqrt{R_{xx}(0)\cdot R_{yy}(0)}} \tag{3}$$

where $R_{xx}$ and $R_{yy}$ are the autocorrelations of $x$ and $y$ respectively. It should be noted that $\left|\rho_{xy}(m)\right| \leq 1$ for all $m$. If $y$ is the same signal as $x$ their cross-correlation will have a maximum for 0. If $x$ and $y$ are linearly related then $y$ will be a shifted and amplified/attenuated version of $x$ and their cross-correlation will have a maximum and their normalised cross-correlation will be 1 for the shift between the two signals. Two signals $x(n)$ and $y(n)$ measured on a linearly vibrating structure will be linearly related. Hence their normalized cross correlation (3) will have a maximum of 1 for the shift between the two signals. When the maximum normalized cross correlation between two signals measured on a structure is less than 1, then this is due to noise and any nonlinearities present in it. For a real structure with close to linear behaviour (when there is not a lot of noise interference) the maximum normalised cross correlation will be close to 1. On the other hand the normalized cross correlation will be 0 or close to 0 for all time lags $m$ if two signals are not linearly related. Thus for a nonlinear structure the cross-correlation is not able to detect the nonlinear dependence between two signals measured on it. In this study we use the maximum normalized cross correlation (4) as a damage metric:

$$\Omega_{xy} = \max_{m} \rho_{xy}(m) \tag{4}$$

## 3 The experiments

10 layers composite laminate beams made by carbon fiber (T300) - epoxy resin (SE 84 SP-Gurit) woven prepreg are manufactured in the Strathclyde University laboratories for the purpose. Prepreg density were 300 g/ m2 and 60% fiber volume. Beam were 350 mm long, 30 mm wide and 1.7 mm thick. Thin beams are chosen because of they allow wide amplitude with a small force, thus a better resolution. Beams were constrained in one edge, like shown in figure 1.

**Figure 1**: clamped edge constrain.

Delamination was introduced artificially by a Teflon sheet in the desired position during hand lay-up process. Thus methodology gives the advantage that delamination can be introduced exactly with the desired size and in the desired position. Two different sizes of delamination were introduced: “long” and “short”. The small one is 115 mm long and the big one is 175 mm long. Three different positions of the delamination along the beam length were tested, and three positions through the specimen’s thickness, as shown in figure 2.

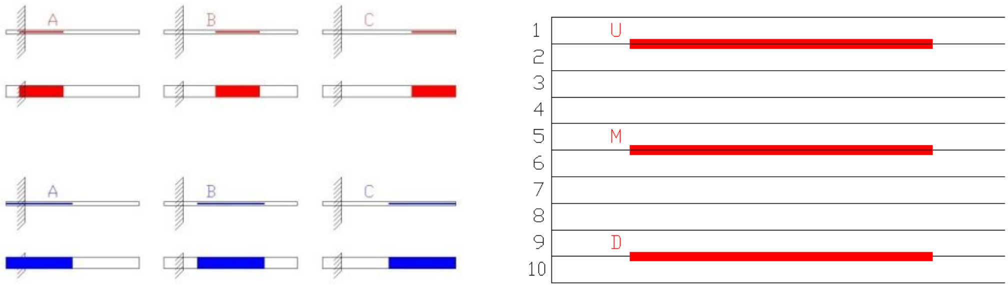

**Figure 2**: delaminated configurations: 3 positions along the length and 3 through the thickness.

Delamination was introduced artificially by a Teflon sheet in the desired position during hand lay-up process. Thus methodology gives the advantage that delamination can be introduced exactly with the desired size and in the desired position. Two different sizes of delamination were introduced: “long” and “short”. The small one is 115 mm long and the big one is 175 mm long. Three different positions of the delamination along the beam length were tested, namely back (starting at the clamped end), middle and front. Beams were clamped in one edge by a G – clamp on a stiff table. and excited by an impulse. Free length was 300 mm. Dynamic response were registered by a piezoelectric accelerometer fixed above the beam. Typical excitation signals for this kind of tests are impulse, broadband, swept sine, and chirp: in this work it is been used an impulse exerted by a metal hammer, hitting the free end of the samples. Three different positions of the accelerometer were explored as well: it was placed at the beginning, in the middle and close to the free end of the beam as presented in figure 3.

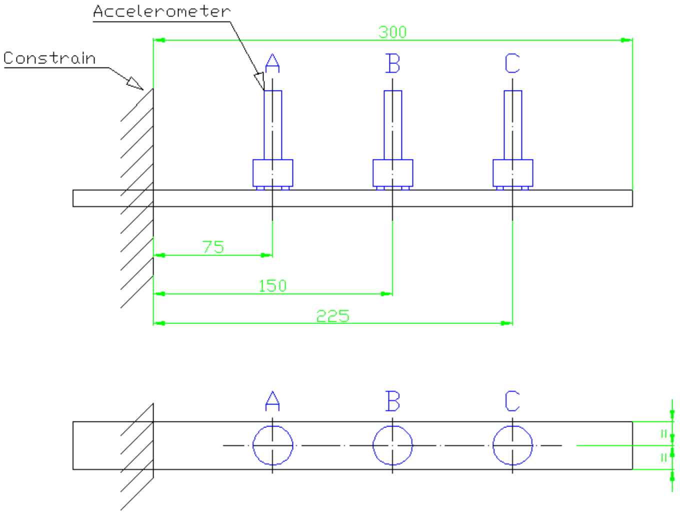

**Figure 3**: accelerometer positions long the beam.

The reason for this choices is that the different vibration modes have different node points where the displacement is null or very close to zero. The middle position is expected to be close to a node point for some modes e.g. the third and the fifth modes, but it is a point of large amplitude displacements for other modes e.g. the first, the second and the fourth mode. Thus it would be appropriate for analyzing some modes. The end position is not expected to be a node point for any of the lower modes for a cantilever beam. Six different configurations of delaminated beams were manufactured, each one of them tested twice, changing the position of accelerometer. Because of possible errors during manufacturing process, 3 identical items for each configuration were manufactured, and each test was repeated 5 times: results are the averages of all the tests.

## 4 Delamination detection in a composite beam

### *4.1 Delamination Detection.*

Below a delamination index based on the maximum normalized cross-correlation introduced in equation (4) is introduced. It represents the relative percentage change in the maximum cross correlation between the baseline (undamaged) condition and a current possibly damaged condition:

$$\omega_{xy}^{j} = \frac{\Omega_{xy}^{in}\Big|^{j} - \Omega_{xy}^{dam}\Big|^{j}}{\Omega_{xy}^{in}\Big|^{j}} \cdot 100 \tag{5}$$

It is applied to the beam described in section 3 for 1) delamination detection and 2) for delamination localization. The maximum value of for all the points $p_j$, (see Figure 4) is used for delamination detection.

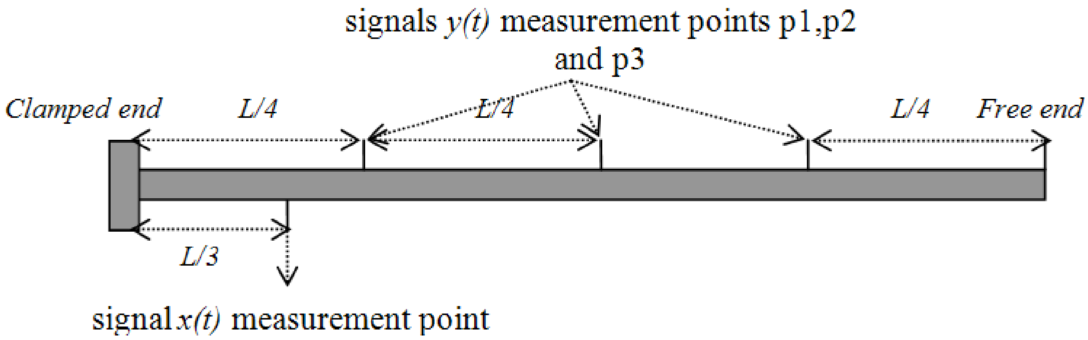

**Figure 4**: measurement scheme.

$$\omega_{xy} = \max_{j} \omega_{xy}^{j} \tag{6}$$

Table 1 gives the results. It represents the mean values of $\omega_{xy}$ obtained over the 20 tests. It can be seen that the cross-correlation index can be used to detect delamination.

| **Delamination location/size** | | **small** | **large** |
|---|---|---|---|
| **left** | upper | 5.11 | 10.11 |
| | middle | 6.02 | 12.00 |
| | lower | 5.00 | 11.21 |
| **centre** | upper | 6.23 | 9.34 |
| | middle | 7.0 | 11.00 |
| | lower | 5.88 | 10.44 |
| **right** | upper | 5.00 | 10.12 |
| | middle | 6.00 | 12.01 |
| | lower | 5.09 | 10.11 |

**Table 1.**Cross correlation-based index $\omega_{xy}$ with delamination

All the changes exceed 5% even for the smaller length of delamination. The changes are more significant, between 10 and 12%, for the larger delamination. Thus it might be possible to use the cross-correlation based index for delamination size estimation. Length estimation is outside the scope of this study so it will not be discussed.

### *4.2Delamination localization*

The signals $y_j$ are measured in three different points, j=1,2,3. These signals will be used for delamination localization purposes. We expect that the above introduced index (equation (5)) will be sensitive to the delamination location and the closer the measurement point to the delamination the more the index will be affected. The results for the correlation-based index are presented in Figures 5a)-c).

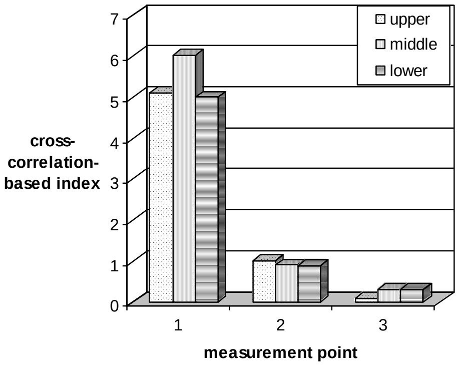

**Figure 5a)**
Cross-correlation index for left delamination

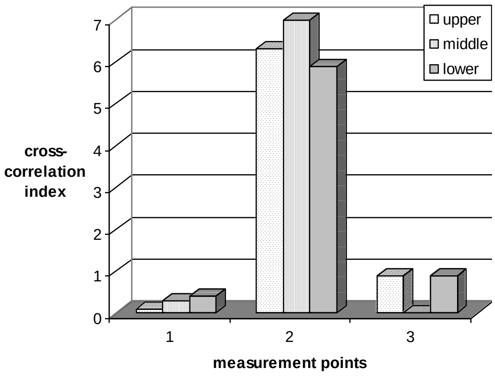

**Figure 5b)**
Cross-correlation index for central delamination

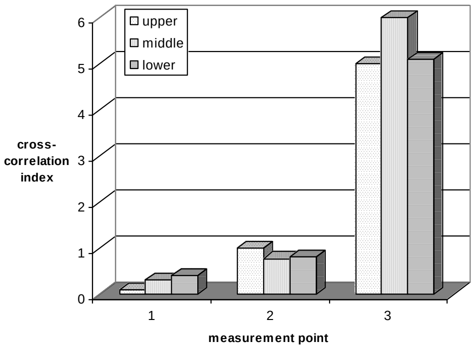

**Figure 5c)** Cross correlation index for right-hand side delamination

They represent the cross-correlation indexes for the three locations of delamination along the length of the beam - left hand side 4a), central 4b) and right hand side 2c)- and also for the tree locations along the beam thickness- upper, middle and lower. It can be seen from the figures that the index used is able to localize delamination rather successfully- the highest indexes correspond to the delamination position.

## 5 Conclusions and discussion

This study suggests a novel concept for delamination detection and localization in composite beams based on the idea of signal cross-correlation. The cross-correlation is a measure for the overall average dependence between two signals measured on a vibrating structure. A method for damage detection and localization is developed based on a suggested delamination index which represents the relative percentage change in the cross-correlation between the baseline and the current structural state. The method is based on the time domain measured structural vibration response and only requires two signals measured in two different points on the structure. In this study the method is demonstrated using the free decay response of a composite laminate beam which is known to demonstrate nonlinear behavior. The method gives good results in terms of delamination detection as well as localization.

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