A simple frequency-based delamination detection and localization method without baseline model

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Abstract. This study suggests a novel non-model-based method for structural vibration-based health monitoring for composite laminated beams which utilises only the first natural frequency of the beam in order to detect and localise delamination. The method is based on the application of a static force in different positions along the beam. It is shown that the application of a static force on a damaged beam induces forces that push the delaminated layers together resulting in an increase of stiffness to a maximum when the static force is applied on the top and the middle of the delamination area. This stiffness increase in turn causes changes in the structural natural frequencies. The method does not require the frequency of the beam in its baseline condition. A very simple procedure for damage detection is suggested which uses a static force applied at only three points along the beam to detect and localise delamination. The method is numerically validated for a simply supported beam, using a finite element model of the beam. Our results show that the frequency variation with the change of the force application point can be used to detect, localize and in the same time quantify very precisely single delamination.

1. Introduction.
Composite materials, are attractive for structural applications and especially in mechanical and aerospace engineering where high stiffness/weight ratio is required. One of the benefits of composite is that they can be used to design structures with required strength and stiffness by changing stacking sequence, fibre orientation and type of fibre. The complexity of composite materials makes it difficult to fully understand their failure mechanism and to detect damage as most of them occur below the

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surface. This resulted in an over-dimensioning by using a safety factor by designer and not taking the full advantages of the cost benefits of composite materials.

The most common and critical defect in composites is the delamination between adjacent layers. The delaminations can occur at the manufacturing phase of the composite material, as a result of an impact by a foreign object during installation or in service, effect of temperature, fatigue loading and machining. Delamination is well known to cause a reduction in stiffness and the strength capabilities of the composite, this reduction varies with composite element size, the delamination size and location. All this changes will affect the vibration behaviour of the composite element.

Delamination cannot be detected by visual inspection, to locate delamination non-destructive inspection methods are required. [1] presented a review on vibration-based model dependent delamination detection methods and health monitoring techniques for composite structures. The sensitivity of the measurement technique used and the parameters chosen for the identification methodology play a key role to damage identification. [2] studied the effect of delamination on the natural frequencies of a laminated composite beam, results showed that an increase in delamination length increases the reduction in the natural frequency. [3] presented the effect length of delamination on the free vibration of composite pre-twisted shells with different stacking sequences. A finite element model has been presented by [4] to analyse the natural frequencies of delaminated composite beams. The effect of the length of the delamination and its position on the bending natural frequencies of a cantilever beam was investigated. An experimental modal analyses was presented by [5] on a simply supported beam to study the effect of delamination on the natural frequencies of composite laminate. In this paper the results from the experiments are checked against a results from a finite element model using the classical beam theory.

Frequency response method in SHM are cheap to implement and can be used to detect damage in a structural component as a defect causing a stiffness reduction will affect the natural frequencies. They can indicate information about the global condition of the system but lot of sensors have to be used to extract some information about the local damaged area.

Most papers that use the natural frequencies for delamination identification are only used for detection and need a baseline frequency. The method we are suggesting is capable to do detect the delamination, localize it and estimate its length. The method that we suggest is based on the application of a force on the beam in different positions. It does not require any baseline frequency. It only needs one application point of the force for detection, two application points are needed for localization and an extra two points are required for length estimation. Nearly all of the mentioned research related to delamination identification is based on the use of several natural frequencies. The method suggested here only uses the first natural frequency of the beam.

2. Methodology.

The method is based on the work of the author [7] where a transverse static force is applied at different position along the damaged beam made of an isotropic material. The damage is detected and located using just the first natural frequency of the beam. No model is assumed and no model is needed for the suggested procedure. The method uses a static force which is applied in different positions along the beam length. The natural frequency of the beam for each position of the static force is measured.

In the case of a composite laminate beam with a delamination, the static force is applied in different location along the delaminated beam which will results in different bending moments values at the centre of the delamination area causing the delaminated layers to be pressed together which will result in a stiffness increase (as compared to the case when no static force is applied) causing the first natural frequency to increase. As for the case of a simply supported beam the maximum bending moment occurs at the point of application of the transverse force, the stiffness of the delaminated beam will go up as the static force position is moved towards the delamination, reaching a maximum value when the force is applied at the centre of the delamination. At this position the deflection of the
beam is maximum and the rotation angle of the deflection is close to zero. So the delaminated layers are pressed closely together which ensures a maximum load transfer.

It has been found in e.g. [6] that tension in a structure increases the natural frequencies, while compression reduces them. In the case of an un-delaminated beam under a transverse static force, as the beam is under bending the part above the neutral line will be under compression while the part beneath the neutral line is under tension. Both forces are equal in amplitude but with opposite signs so their effect on the natural frequencies is cancelled and the natural frequency of the undamaged beam with the static force is the same as the one for the same beam with no force applied. From this we can conclude that the frequency of the delaminated beam with a static force applied on centre of the delamination will increase as compared to the frequency measured without any force applied, to a maximum value equal of that of the undelaminated beam and will never go beyond that.

In this study we use a percentage frequency shift which is introduced as follows:

$$
\Delta f = \frac{f_f - f_{nf}}{f_{nf}} \times 100
$$

(1)

Where $f_{nf}$ is the frequency with no force applied and $f_f$ is the frequency with a static force applied for the delaminated beam correspondingly.

2.1. Detection

The detection is done by applying a static force in one position along the beam and comparing the first natural frequency of the beam to the one with no static force applied. We suggest that the best position for the static force is at midspan because in this case the bending moment at any point of the beam is quite substantial and will have an effect on any delamination along the length of the beam. As a result if there is delamination in the beam there will be a frequency shift when the force is applied in the middle. If there is no frequency shift this will mean there is no delamination or the delamination is rather small or close to the supports of the beam. In such a case other points of application to the left and the right of the the centre are used to look for smaller delamination away from the centre of the beam.

2.2. Localization

From the finite element analysis results it has been found that the frequency shift variation with the static force position is almost linear, but as the static force position position reaches the edge of the delamination and moves toward its centre the line changes its gradient and become steeper. Fig(3) shows the frequency shifts for a number of application points of the static force for one such a case. For the localization, the static force is applied at two symmetric points about the middle of the beam and preferably close to the supports, e.g. at about L/5 to L/4 from the ends of the beam. Let's denote by A an B these two points (see Fig 1). If the frequency shift when the static force is at A is bigger than the one when the force is at B, this means that the centre of the delamination is to the left of the middle of the beam and vice versa. The intersection of the segments $\Delta f_A$, $\Delta f_0$ and $\Delta f_B$, $\Delta f_c$ gives point P whose projection on the beam indicates the centre of the delamination (see Fig 1). The distance from the left hand support and the centre of the delamination is given by expression (2) where $a$ and $b$ are the distances of points A and B from the left hand support respectively.

$$
x_d = \frac{\Delta f_B}{(L-b)} \left( \frac{\Delta f_B}{L-b} + \frac{\Delta f_A}{a} \right)
$$

(2)
2.3. Quantification.
To estimate the length of the delamination, the static force is applied at two additional points M and N to the left of the centre of the delamination (see Fig 1). The corresponding frequency shifts, denoted by Δf_M and Δf_N, define the line of the frequency changes over the delamination. The intersection of the lines Δf_A - Δf_O and Δf_M - Δf_N gives the point D which indicates the edge of the delamination. Once we know the centre and the end of the delamination, its length can be determined. The distance between the left hand support and the edge of the delamination is given by Eq(3).

\[ x_c = \frac{(n \Delta f_M - m \Delta f_N) a}{(\Delta f_M - \Delta f_N) a - \Delta f_A (m - n)} \]  

(3)

Where a, m, n are the distances from the left hand support and the points A, M, N respectively. The length of the delamination d is given by the following expression.

\[ d = 2(x_d - x_c) \]  

(4)

Figure 1: The beam with the delamination and the frequency shift lines.

3. The composite beam model.
The material used is a unidirectional carbon/epoxy AS4D/9310 composite with E1 = 133.86 GPa, E2 = E3 = 7.706 GPa, G12 = G13 = 4.306 GPa, G23 = 2.76 GPa, ν_{12} = ν_{13} = 0.301, ν_{23} = 0.396 and ρ = 1520 kg/m³. The geometrical parameters of the specimen are length L = 0.35 m, thickness H = 0.002 m, width b = 0.03 m.
The 10-layered structure has \([0/90_/0/90_/0]\) as stacking sequence. All the cases are modeled as a through width delamination and the delaminated layers are free to move and are not constrained. Due to the fact that modal analysis in Ansys cannot deal with nonlinearities, gaps or contacts, The undamaged beam was analysed using modal and transient analysis to make sure that both methods give the same results. On the delaminated beam a transient analysis was conducted and the results are compared to the ones from the prestressed transient analysis when an 8 N static force is applied.

![Fig 2: Schematic of the composite Beam](image)

4. **Results and discussion.**

All the cases considered and the results are summarized in Table 1. The points A,B, are chosen to be at 0.1L and 0.9L from the left hand support of the beam while N and M are located at .025L and 0.05L from the centre of delamination respectively see Fig 1. The length of delamination that can be estimated is dependant of the choice of points M and N because they should be on the delamination itself. The smallest delamination length that can be estimated is equal to twice the distance between the centre of the delamination Q and point N, so if point M is chosen to be on Q and point N to be as close to Q as possible so the length of a shorter delamination can be estimated. The estimated delamination lengths and the associated errors when compared to the real length value are presented in Table 1. It can be seen that for all cases that the frequency shift \(\Delta f_0\) are quite high which indicates the existence of a delamination. This can be considered as an indication of the reliability of the detection methodology by applying a static force at mid span of the beam. The position of the centre of the delamination was precisely localised for all cases using equation 2, the delamination was quantified by estimating its length using equation 3 and 4 with a maximum error of 7.66% when compared to the real value.
Table 1: Estimated delamination location and length for cases 1-12.

| cases | a_d (L) | L_d (L) | H_d (L) | ΔF_a (%) | ΔF_m (%) | ΔF_l (%) | ΔF_r (%) | Est x_d (L) | Est x_s (L) | Est d (L) | Error (%) |
|-------|--------|--------|--------|----------|----------|----------|----------|-------------|-------------|-----------|-----------|
| 1     | 0.50   | 0.10   | 0.50   | 1.19     | 1.19     | 5.83     | 5.30     | 6.39        | 0.50        | 0.45      | 0.10      | 2.13      |
| 2     | 0.50   | 0.10   | 0.30   | 1.11     | 1.11     | 5.71     | 5.09     | 6.28        | 0.50        | 0.45      | 0.11      | 7.35      |
| 3     | 0.30   | 0.10   | 0.50   | 1.65     | 0.73     | 4.96     | 4.17     | 3.86        | 0.30        | 0.25      | 0.11      | 7.66      |
| 4     | 0.30   | 0.10   | 0.30   | 1.74     | 0.75     | 5.22     | 4.25     | 3.82        | 0.30        | 0.25      | 0.09      | 6.94      |
| 5     | 0.50   | 0.20   | 0.50   | 1.13     | 1.13     | 6.09     | 5.53     | 6.76        | 0.50        | 0.40      | 0.19      | 4.04      |
| 6     | 0.50   | 0.20   | 0.30   | 1.16     | 1.16     | 6.39     | 5.81     | 6.98        | 0.50        | 0.40      | 0.20      | 0.86      |
| 7     | 0.30   | 0.20   | 0.50   | 1.64     | 0.69     | 5.75     | 4.93     | 4.11        | 0.30        | 0.20      | 0.19      | 3.25      |
| 8     | 0.30   | 0.20   | 0.30   | 1.70     | 0.72     | 5.93     | 5.09     | 4.24        | 0.30        | 0.20      | 0.20      | 1.88      |
| 9     | 0.50   | 0.30   | 0.50   | 1.32     | 1.32     | 7.91     | 7.25     | 8.57        | 0.50        | 0.35      | 0.30      | 0.51      |
| 10    | 0.50   | 0.30   | 0.30   | 1.36     | 1.36     | 8.14     | 7.46     | 8.82        | 0.50        | 0.35      | 0.30      | 0.98      |
| 11    | 0.30   | 0.30   | 0.50   | 1.81     | 0.78     | 7.23     | 6.33     | 4.78        | 0.30        | 0.15      | 0.30      | 1.33      |
| 12    | 0.30   | 0.30   | 0.30   | 1.87     | 0.80     | 8.67     | 7.49     | 4.96        | 0.30        | 0.15      | 0.30      | 1.07      |

Figure 3: Frequency shift vs Static force position for case 1
5. **Conclusion.**

This paper suggests a very simple method for complete delamination identification in composite beams which is based on the first natural frequency of the beam and no base model is needed. The procedure involves the application of a static force which is applied in different positions along the composite beam. The result show that the delamination locations obtained using the FE model are the same as the real ones. The estimated delamination lengths are very close to the real values with a maximum error of 7.66 %. The method is being developed for the case of multiple delaminations.

6. **References.**

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