VIBRATION MONITORING OF COMPOSITE LAMINATES WITH DELAMINATION DAMAGE

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1 Introduction

Fibre-Reinforced Polymer (FRP) composites are widely used in aeronautical, marine and automotive industries, because of their excellent mechanical properties, low density and ease of manufacture. However, due to their low strength in the through-thickness direction, FRP composite laminates are susceptible to delamination damage. Delaminations may not be visible from surface but have a significant detrimental effect on bending stiffness and compressive load bearing capacity. Therefore, it is important to detect the presence of delaminations at an early stage.

The aircraft industry currently uses non-destructive inspection techniques such as ultrasonic testing and thermography for delamination detection in composite laminates. Although quite effective, these non-destructive techniques have the disadvantage that they require the aircraft to be grounded for inspection, which has heavy economic penalties. Aircraft maintenance is entering a new era where the industry is seeking to implement structural health monitoring (SHM) systems, which can be applied on-line, in real time, while the aircraft is in operation. In addition to saving maintenance costs, SHM systems also offer the benefit of increased safety as the occurrence of damage can be detected in real time. Among the many new techniques proposed as potential SHM systems such as Fibre Optic Sensors, Comparative Vacuum Monitoring and Acoustic Emission, Vibration Monitoring is one of the most promising[1]. Vibration based damage detection is based on the principle that damage in a structure reduces its local stiffness, which results in changes in vibration parameters such a s natural frequencies, mode shape and damping ratio[2]. By monitoring changes in these parameters we can detect the presence and assess damage. The monitoring of mode shapes requires measurements at multiple locations, is time consuming and prone to noise. Damping parameters are notoriously difficult to measure, being sensitive to environmental conditions. In comparison, natural frequencies require only single point measurement, and can be monitored with greater, accuracy, ease and reliability [3].

While there is considerable literature on research on crack detection using vibration techniques in metallic panels and damage in civil structures[4-8], no many studies have been reported on detection of delaminations in laminated composites using vibration monitoring [9]. Okafor et al [10] used laminate theory developed by Tracy [11] and generated a database relating frequency shifts to damage location and size in cantilever composite beams to train a neural network algorithm, which they applied to predict delamination sizes from measured frequency shifts in experimental beams. Yam et al [12] proposed a method which combined changes in measured modal damping with computed modal strain energy distributions to predict the location of internal delaminations in multilayer composite plates.

One of the disadvantages of frequency monitoring is that while a shift in frequency easily identifies the presence of damage, the determination of the location and the severity of the damage is not easy to accomplish. The latter requires solution of the inverse problem, viz., identifying the parameters indicating the location and severity of damage from measured changes in modal frequencies. When several unknown parameters need to be identified this normally requires the application of advanced system identification or optimisation techniques such as neural networks or genetic algorithm [13]. However when only two or three parameters are needed to assess the damage, such as location along the length of the beam and the depth of a through width crack in a beam, this can be easily achieved using a graphical technique. The graphical technique was first proposed by Adams and Cawley [14], who showed that by plotting a crack size index versus crack location for the first three modes of a straight bar, the possible damage size and location can be estimated. Since then many other researchers have employed a similar technique for solving the inverse problem, but mostly for estimating location and size of transverse or through thickness cracks in isotropic (metallic) beams.

In the present work, the graphical approach is extended to damage detection in delaminated beams and for the first time the application of the technique to determine three parameters, the location along the axis of the beam and the width of the delamination as well as the interface at which it occurs, is presented. The method is validated using several numerical test cases.

2 Methodology

2.1 Detection of delamination at known interface

Before the inverse problem can be solved, we have to first address the forward problem, i.e. determine changes in modal frequencies of the structure as a function of the damage parameters. This can be done either by theoretical analysis or through numerical simulation or from experimental data. In the case of the cantilever beam problem being used for illustration here, the data was generated using finite element modelling. For delaminations extending over the full width of the beam, if the interface at which the delamination occurs is known, then the shift in modal frequency due to the damage can be expressed as a function of its location "x" along the length of the beam and its size "a" as:

$$\Delta\omega_n = f_n(a, x). \quad (1)$$

where 'n' indicates the mode number. The functions "f_n" are different for different modal frequencies and can be graphically depicted as surface plots of "$\Delta\omega_n$" as a function of "a" and "x" for each mode.

Assuming that we have measured natural frequency changes for a delaminated beam for several modes, $\Delta\omega_1$, $\Delta\omega_2$, $\Delta\omega_3, \ldots$, then by substituting these known values on the left side of equation (1), a series of functions can be obtained:

$$\Delta\omega_1 = f_1(a,x); \Delta\omega_2 = f_2(a,x); \Delta\omega_3 = f_3(a,x) \ldots (2)$$

Since $\Delta\omega_1$, $\Delta\omega_2$, $\Delta\omega_3$ are constants, we may rewrite the above functions as:

$$x = g_1(a); x = g_2(a); x = g_3(a) \quad \ldots \quad (3)$$

If we plot the curves represented by equations (3) on the a-x plane, they will all intersect at a common point which identifies the location and the size of the delamination which has caused the frequency shifts $\Delta\omega_1$, $\Delta\omega_2$, $\Delta\omega_3, \ldots$ in modes 1,2,3,… respectively.

The above steps can be summarised as follows:

Step 1: Draw surface plots of frequency shifts as functions of delamination size "a" and location along the beam "x" for each mode with data obtained from theory, FE or experimental testing.

Step 2: Draw planes representing constant values of the measured frequency shifts in each mode and find their intersections with the corresponding surface plots.

Step3: Replot the intersection curves of all modes on the size vs. location plane, and find the point at which all curves intersect.

Steps 1 to 3 are illustrated with a typical example in Figures 1 and 2. The surface plots of the frequency shifts as functions of the normalised delamination size "a/L" and normalised location "x/L" for a 0/90/90/0 CFRP cantilever beam are shown in Figures 1(a), 1(b) and 1(c) for modes 1,2 and 3, respectively (Step 1). Also shown in the figures in red are curves indicating the intersection of each surface plot with the plane representing a constant "measured" value of frequency shift in the corresponding mode (Step 2). These curves are replotted with "x/L" along the x-axis and "a/L" along the y-axis (Step 3) in Figure 2. It can be seen that there are at least two points at which the curves from the first three modes intersect, but when we add the curve representing a constant frequency shift in Mode 4 also, there is only one point in Figure 2 where the curves of all four modes intersect. This point represents the estimated location and size of the delamination which caused the "measured" frequency shifts in the first four modes. It may be noted that because of the large number of peaks and troughs, especially in the higher modes, it may not be sufficient to use only three modes and in general, the method is more reliable, the larger the number of modes we employ. In real situation all the curves may not pass through a single point due to measurement errors and numerical errors in the generated data base. Thus, in practice it is more expedient to replace the intersection point with that point at which the curves come closest to each other, which is determined by calculating the point which gives the minimum value for the standard deviation between the curves.

2.2 Detection of delamination at unknown interface

In general, the z-location of the delamination, i.e. the interface at which the delamination has occurred is also an unknown. In this case we have to determine three unknown parameters, the x-location, the size "a" and the interfacial location. The procedure to find all three unknowns simultaneously is as follows:
Step 1: Repeat step 1 in section 2.1 for each interface, i.e. generate data and draw surface plots of frequency shifts vs. delamination size and x-location for each mode *for delaminations located at each interface*.
Step 2: Repeat step 2 in section 2.1 for each interface, i.e., draw planes representing constant values of the known (measured) frequency shifts in each mode and find their intersections with the corresponding modal surface plots, *for each interface.*
Step3: Repeat step 3 in section 2.1 for each interface, i.e. replot the intersection curves of all modes on the size vs. location plane, and find the values of "x" and "a" for which the standard deviation between the curves is a minimum, *for each interface*.
Step4: Compare the minimum standard deviations calculated for each interface in step 3, and identify the minimum of these. The interface at which the most minimum standard deviation occurs is the likely location of the delamination and the corresponding values of "x" and "a" its location along the length of the beam and its size.
The validity of the above procedure is demonstrated in the following sections using finite element modelling (FEM) to simulate delaminations at different interfaces in an eight layered quasi-isotropic composite beam. The data from the FE is also used as test cases to assess the validity and the accuracy of the proposed damage assessment method.

3 Finite Element Modelling

The finite element modelling for simulation of the delaminated beams and extraction of the natural frequencies was conducted using the commercial software ANSYS12. The composite beam was modelled as a cantilever with length 250 mm, width 20 mm and a symmetric quasi-isotropic lay-up of [0/+45/-45/90]s. The material of the beam was taken to be carbon fibre reinforced epoxy with stiffness values E_1=138GPa, E_2=8.96GPa and E_{12}=7.1GPa, and Poisson's ratio ν_{12}=0.30. The layer thickness is 0.125 mm and the density of the material 1901.5 kg/m^3. The beam was modelled with Layered Solid185, eight-node layered structural solid element with three degrees of freedom at each node. A mesh sensitivity study was first conducted to determine the optimum number of elements to be employed for a typical delaminated beam model. The final model employed 200 elements along the length, 16 along the width and one element for each layer of the laminate. For the delaminated beams, the model typically consisted of four segments, the two undamaged regions and the two sub-laminates above and below the delamination. Standard Contact elements were introduced between the surfaces of the two sub-laminates, which allowed neither penetration nor separation between the sub-laminate structures.
Due to symmetry in the lay-up, it was necessary to model delaminations only at four interfaces, interface 1 (mid-plane) to interface 4 (outermost interface) as shown in Figure 3. At each interface, the delamination location is varied from 20% to 80% of the beam's length (measured from the fixed end) with increments of 2% (total of 31 locations). The delamination size is varied from 2% to 40% of the beam length with 2% increments (total of 20 size cases) at each location. Thus, including the case of the undelaminated beam, a total of 2481 simulations were run.
Eigen value modal analysis was carried out to extract the natural frequencies of the flexural bending modes using the Block Lanczos method (torsion and in-plane bending modes are discarded). Total 18 hours were spent to run all the simulations. The bending frequencies obtained from the modal analysis were transferred to a Matlab programme to draw 3D surface plots as in Step 1 of section 2.2. A further 12 cases were run in ANSYS as test cases to ascertain the validity and accuracy of the methodology developed for solution to the inverse problem.

4 Results and Discussion

The twelve randomly chosen test cases employed for validation of the methodology are listed in Table 1. Three delaminations were simulated at each of the four interfaces, at locations ranging from 24% to 72% of the beam length and with sizes between 3.6% and 36% of the beam length. The shifts in frequencies from those of the undelaminated cantilever beam estimated by the FE analysis for the first four modes are also listed in Table 1. These frequency shifts were employed to determine the intersections of the planes representing them with the surface plots created from the data base for each mode for delaminations assumed to be located at each intersection, as outlines in step 2 of section 2.2. The minimum standard deviations between the curves of the four modes at each interface (indicating the intersection points and hence the possible location and size of the damage if the delamination were located at that interface) were then calculated (step 3, section 2.2). These are listed in Table 2 for each test case. It may be noted that in some cases, no common intersection point between the curves of the four modes could be found; these are indicated by 'Nan' in the table. The smallest value among the standard deviations obtained at the four interfaces for each test case is highlighted in bold for easy identification. Using these smallest values as indicators of the interface at which the delamination is predicted, the intersection point identified by the minimum standard deviation at this interface is employed to determine the delamination size (a/L) and its location along the length (x/L). The predicted interface location, delamination size and location are listed for the 12 cases on the right most columns in Table 12. Only in one case (test case 7) was the prediction of the interface erroneous; the smallest minimum standard deviation was obtained for interface 2, while the delamination was located at interface 3. This appears to be due to the closeness between the values of the standard deviations at interfaces 2 and 3 for case 7, which could be attributed to the fact that Case 7 had the second smallest delamination size, which was located closed to the fixed end of the cantilever beam. It is, however, encouraging that even when the interface prediction is wrong, the errors in the predicted size and x-location of the delamination from their actual values are very small; the error in x-location is less than 0.15% and the error in size prediction is 0.33%. The comparisons between the actual and predicted x-locations and the actual and predicted delamination sizes are presented graphically in Figures 4(a) and 4(b) respectively. The largest error in prediction of delamination size (of the order of 1%) occurs in Case 5, which has the smallest delamination size. In all other cases the errors in the size predictions are less than 0.35%, while the maximum error in estimation of delamination location is only 0.15%.

5 Conclusions

A simple 3-step graphical detection method is developed for successfully detecting delamination in composite beams through monitoring changes in natural frequencies. The numerical simulations show that this method can be successfully employed to predict the delamination size, lengthwise location and the interface at which the delamination occurs, with considerable accuracy. Prediction errors of location and size are within 0.35%, except in one case, and the prediction of interface location is correct in eleven out of twelve cases. Of course, such great accuracy is only possible because the test cases are simulated by numerical modelling, which was employed to generate the database. In applying this to real situations for estimating delaminations sizes and locations measured frequency shifts, the accuracy of the method is likely to be much lower. Nevertheless, the test cases using numerical simulation successfully prove the validity of the method and its potential for application to real situation. Further research is being conducted to validate the method by experimental testing on composite beams with simulated delaminations and for its extension to the detection of multiple delaminations occurring sequentially.

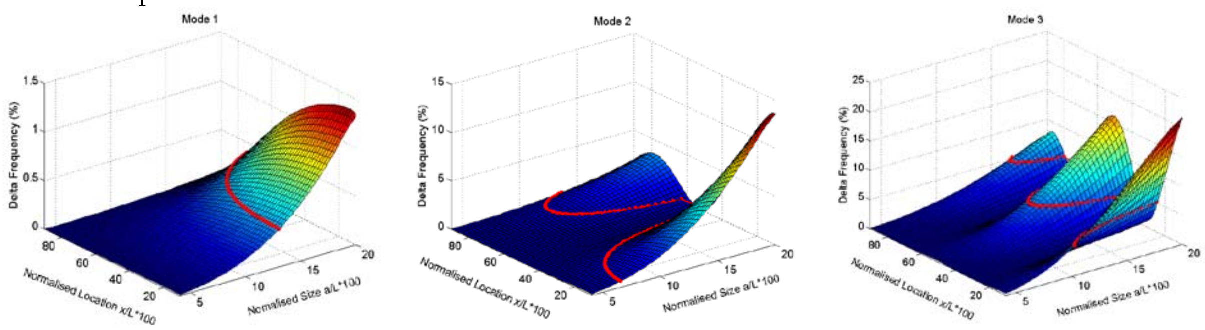


Fig.1. Surface plots of frequency changes with damage size and location for mid-plane delamination in composite beam for first three modes (Steps 1&2)

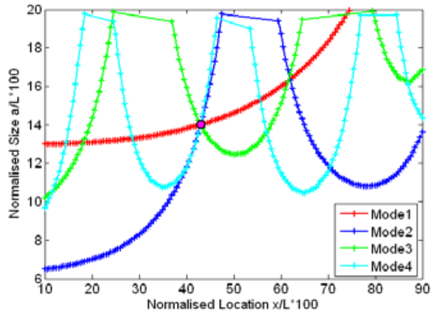


Fig.2. Intersection curves of modes 1to 4 for determination of delamination size and location (Step3)

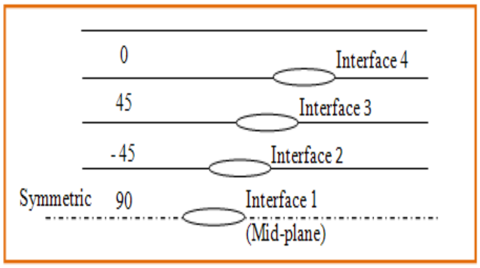
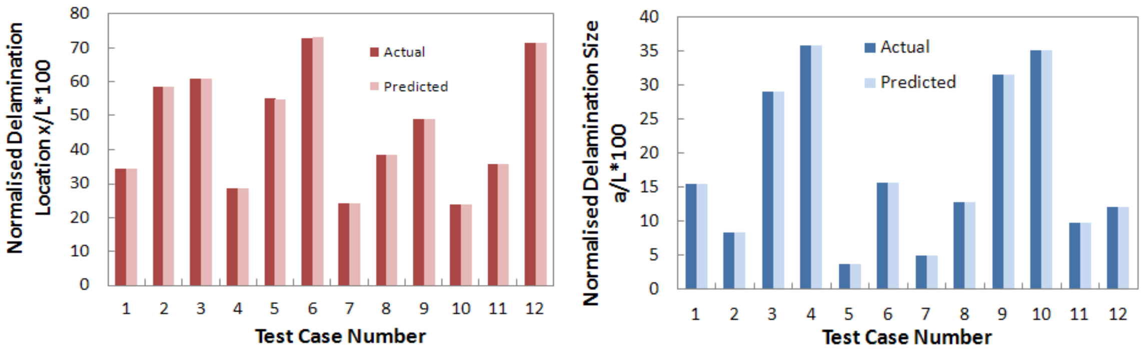


Fig.3. Schematic of quasi-isotropic beam modelled showing interface designations



(a) (b)

Fig.4 Comparison of Predicted Delamination location and Size with Actual values for Test cases 1 to 12

Table 1 Frequency changes from FEA in the first four modes for the 12 test cases

Test Case no.	**Actual Interface**	**Actual Location x/L*100**	**Actual Size a/L*100**	**Frequency Change Δω/ω (%)**			
				Mode 1	**Mode 2**	**Mode 3**	**Mode 4**
1	1	34.5	15.4	16.45	13.05	13.94	21.49
2	1	58.7	8.3	2.35	14.42	7.06	6.75
3	1	61	29	9.57	29.76	39.88	35.82
4	2	28.6	35.8	34.98	40.31	25.83	37.04
5	2	55	3.6	1.189	6.83	1.28	3.91
6	2	73	15.5	1.17	13.63	19.16	20.95
7	3	24.2	4.8	6.14	0.29	4.08	4.09
8	3	38.5	12.6	8.31	9.64	7.99	8.22
9	3	49	31.5	13.16	24.22	32.30	20.78
10	4	24	35	8.42	14.79	10.66	12.36
11	4	35.6	9.6	1.20	1.17	1.58	0.92
12	4	71.4	12	0.11	1.54	2.82	2.28

Table 2 Standard deviations for delaminations at interfaces 1 to 4 and predicted locations

Test Case no.	**Standard deviations at Intersection Points**				**Predicted Interface**	**Predicted Location x/L*100**	**Predicted Size a/L*100**
	Interface1	**Interface2**	**Interface3**	**Interface4**			
1	**0.0266**	0.439	1.093	*Nan	1	34.467	15.404
2	**0.117**	0.321	0.757	9.878	1	58.675	8.286
3	**0.116**	1.606	Nan	Nan	1	60.911	28.967
4	0.817	**0.045**	Nan	Nan	2	28.556	35.771
5	0.071	**0.034**	0.105	9.381	2	54.978	3.637
6	0.567	**0.015**	0.678	Nan	2	73.031	15.539
7	0.104	**0.093**	0.116	7.52	**2**	24.166	4.816
8	0.587	0.288	**0.03**	2.523	3	38.524	12.598
9	1.815	1.093	**0.06**	Nan	3	49.007	31.49
10	1.029	0.706	0.426	**0.0**	4	24	35
11	0.437	0.102	0.351	**0.04**	4	35.582	9.5958
12	0.314	0.346	0.467	**0.028**	4	71.424	12.02

*"Nan" indicates no intersection point found at the particular interface.

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