EVALUATION OF METRICS AND TECHNIQUES FOR THE DETECTION OF DELAMINATION IN COMPOSITE STRUCTURES USING PIEZOELECTRIC SENSORS

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Abstract. *The use of piezoelectric materials in the function of distributed sensors and actuators for the control and monitoring of structural vibrations has enormous potential for application in the aeronautical, aerospace, automotive and electronics. The use of integrated piezoelectric sensors for structural health monitoring (or damage detection), in particular, has evolved greatly over the last decade. Consequently, the numbers of techniques used for this purpose are highly diverse. Among them are techniques that evaluate the effect of damages on low frequency modal parameters, especially natural frequencies and mode shapes, or on medium-high frequency measurements of electromechanical impedance/admittance. The objective of the present work is to perform, with the aid of a 2D ANSYS finite element model, an analysis of different techniques for the detection of position and size of a delamination in a composite structure using piezoelectric patches. Several metrics and techniques are evaluated in terms of their capability of identifying, with relative accuracy, the presence, location and severity of the damage. Results show that both modal and impedance-based techniques are able to identify the presence of the delamination-type damages, provided the piezoelectric patches are close enough to the damage. It is also shown that impedance-based techniques seem more effective than modal ones for the detection of delamination position and size.*

Keywords: *Smart Structures, Piezoelectric Materials, Finite Element Method, Structural Health Monitoring, Monitoring Techniques*

1. INTRODUCTION

Structural health monitoring (SHM) may be considered as a continuous procedure for the detection of adverse modifications, denoted as damage, in the structure that may deteriorate its performance (Inman *et al.*, 2005). Structural damage may take several forms, such as cracks and delaminations, depending on the operating and environmental conditions. The main interest of SHM techniques is to identify the damage in its initial stages and avoid catastrophic failures or manufacturing interruptions. The SHM techniques may be classified in terms of their capabilities in terms of damage detection. By increasing difficulty, the expected capabilities of a SHM technique would be first to determine the presence of damage in the structure, then to determine the damage location, then to quantify the damage severity, then to predict the remaining service life of the structure (Doebling *et al.*, 1998). Some more advanced capabilities could be added, such as the prediction of future behavior of damaged structure and the mitigation of the effects of damage (self-healing structures) (Inman and Grisso, 2006).

Currently, the standard non-destructive evaluation are performed manually by specialized technicians, using ultrasonic waves, magnetic fields, liquid penetrant, among others techniques. These normally require that the structure or equipment to be evaluated should be out-of-service. On the other hand, the recent development of smart structures allows to distribute highly integrated sensors and actuators over the structure which can then be used to interrogate and monitor the response of the structure in real-time. Several techniques can benefit from integration provided by smart structures. Among the SHM techniques using smart structures, there are those based on modal parameters, such as resonance and anti-resonance frequencies, mode shapes and their derivatives (Doebling *et al.*, 1998; Maia *et al.*, 2003; Benjeddou *et al.*, 2006), those based on frequency response, such as impedance or admittance measurements (Park *et al.*, 2003; Zagrai and Giurgiutiu, 2001), those based on guided waves, such as Lamb waves (Giurgiutiu and Cuc, 2005), and those based on time series analysis (da Silva *et al.*, 2008).

Several recent works focus on the definition of the parameters of impedance-based techniques, such as the response type (impedance, admittance, elastance,...), component (real part, imaginary part, amplitude,...), frequency range and damage metric (root mean square, *p*-norms, correlation,...) to be used in the comparison of the responses of damaged and undamaged structures. Although most studies suggest that real part of impedance or admittance should be more effective for damage detection, the best performing damage metric and frequency range are still very problem dependent and are normally defined by trial and error.

In particular, the detection of delamination in laminate structures has proven to be a particularly difficult task, since several traditional SHM techniques, like visual inspection and liquid penetrant, are inefficace in this case. Besides, otherwise effective techniques like ultrasonic or guided waves are hindered by the multiple reflections due to the layered interfaces. However, vibration-based and impedance-based techniques seem to be less afected by the layered characteristic of such structures and, thus, have been applied to delamination detection (Bois and Hochard, 2004; Zou *et al.*, 2000).

The objective of the present work is to perform, with the aid of a 2D ANSYS finite element model, an analysis of different techniques for the detection of position and size of a delamination in a composite structure using piezoelectric patches. Several metrics and techniques are evaluated in terms of their capability of identifying, with relative accuracy, the presence, location and severity of the damage.

2. FE MODELING OF A LAMINATE BEAM WITH DELAMINATION AND PZT SENSORS

In this section, a finite element (FE) model for a cantilever laminate beam, featuring the inclusion of a delamination at the interface of two layers and two piezoceramic patches bonded to the surface of the beam, is presented. The laminate beam is composed of six cross-ply layers $(0/90/0)_s$ of fiber-reinforced Carbon Epoxy material AS4/3501-6. Two piezoelectric patches made of through-thickness poled PZT-5H ceramic material are bonded to the upper surface of the laminate beam. The geometric properties of the cantilever laminate beam are presented in Figure 1.

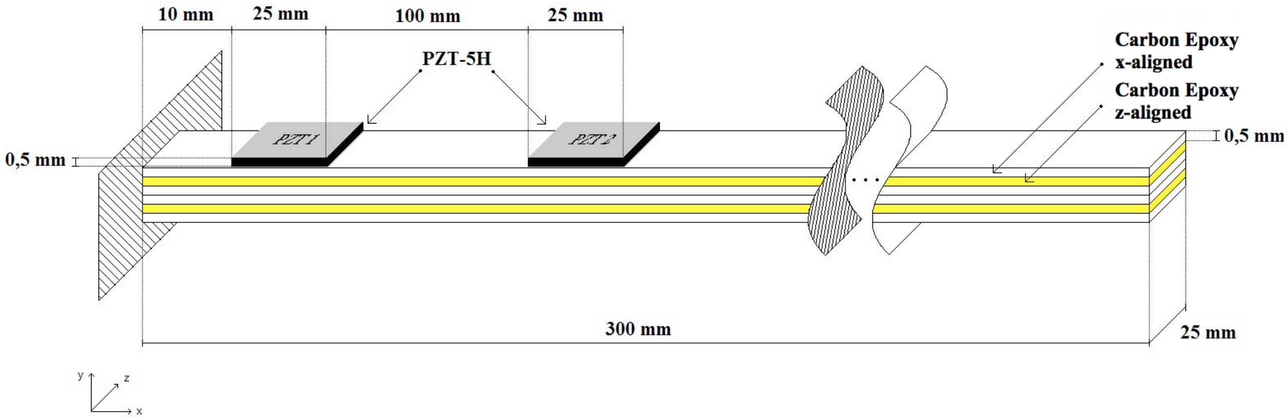

Figure 1. Geometric properties of the cantilever laminate beam.

A delamination is included in the interface between the first and second layers, from top to bottom, of the cantilever beam. This is done by not bonding (connecting) the delaminated part of the interface layer. Three sizes (lengths), 10, 20 and 30 mm, and three positions, 60, 85 and 110 mm from its center to clamped end, are considered for the delamination.

The Carbon Epoxy layers are modeled using eight-node plane elements (PLANE82), with two degrees of freedom (dof) per node that are the displacements in x and y directions. The piezoceramic patches are modeled using eight-node coupled plane elements (PLANE223), with three dof per node that are the displacements in x and y directions and the electric voltage. The constitutive matrices for both materials should be rotated properly so that they correspond to the x (0^o) and z (90^o) fiber direction, in the case of the Carbon Epoxy layers, or the through-thickness y poling direction, in the case of piezoceramic patches. Notice that both PLANE82 and PLANE223 elements do not represent nodal rotations.

The model geometry is constructed from rectangular areas as shown in Figure 2. The model for the damaged (delaminated) structure is obtained by not connecting part of the two first composite layers. This is done by dividing these two layers in three rectangular areas each, so that the central areas (A5 and A6 in Figure 2) for the two layers are not connected (bonded or glued) to represent the delamination. The other areas are connected in all interfaces. The contact between delaminated surfaces is not represented in this work but should be accounted for in future works.

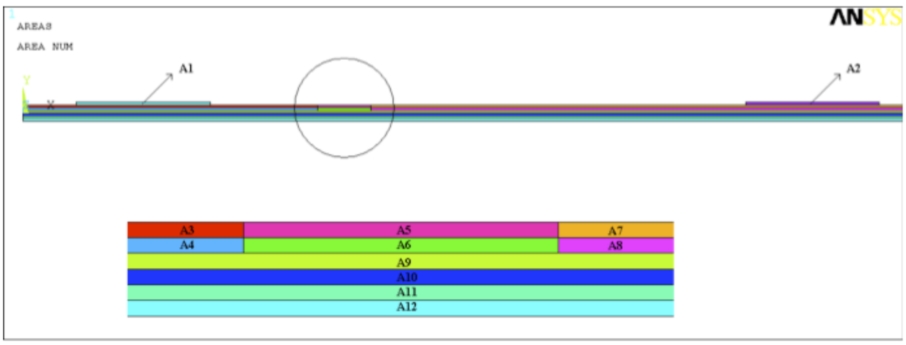

Figure 2. Geometric construction of FE model for the cantilever laminate beam with a 10 mm delamination located at 60 mm from the clamped end.

The FE mesh is built using retangular elements with length 1 mm and thickness 0.5 mm for all areas except for the areas corresponding to the two upper layers and piezoelectric patches for which the rectangular elements are refined in the thickness-direction to 0.25 mm. The objective of using a uniform FE mesh is to minimize its effect on the comparison of the responses for each damage configuration and undamaged structure. After meshing of the rectangular areas, the pairs of superposed nodes at all interfaces, except the delaminated one, are merged into single nodes to guarantee perfect coupling of x and y displacements at these interfaces.

The nodal electric voltage dof at the upper surface of each piezoelectric patch are connected, using the *Couple DOFs* tool of ANSYS, to ensure equipotential surfaces representing the conductive electrodes of the piezoelectric patches. On the other hand, those voltage dofs at their lower surfaces are set to zero, representing grounded electrodes.

In order to evaluate the modal damage metrics, the natural frequencies of the damaged and undamaged structures must be evaluated. Two electric boundary conditions are considered for each piezoelectric patch, open-circuit and short-circuit. The short-circuit boundary condition is obtained by setting the coupled voltage dofs at upper surfaces of each piezoelectric patch to zero, while for the open-circuit condition these dof are free.

Three modal analyses are performed for each undamaged and damaged structures depending on the electric boundary conditions of the two piezoelectric patches: 1) the two patches are in short-circuit; 2) the first patch is in open-circuit while the other is in short-circuit; and 3) the second patch is in open-circuit while the other is in short-circuit. For each case, the first one hundred natural frequencies are evaluated using Block Lanczos algorithm. Figure 3 presents some vibration modes for one of the damaged structures considered.

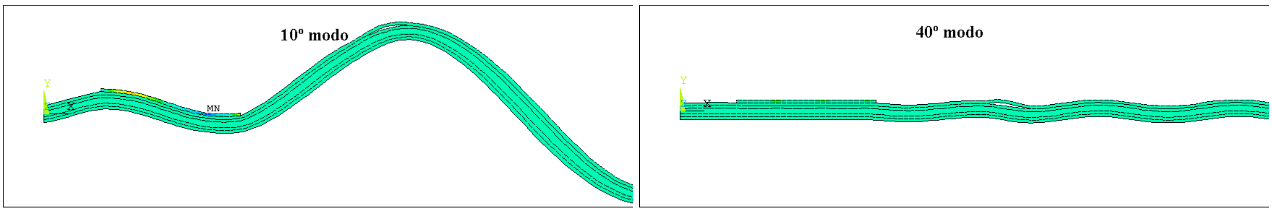

Figure 3. Selected vibration modes for the cantilever laminate beam with a 10 mm delamination located at 60 mm from the clamped end.

The frequency responses of the laminate structure are evaluated using the two piezoelectric patches, that are used as both sensors and actuators. This is done using a harmonic analysis in ANSYS for which an eletric charge is applied (input) at the upper electrode of each piezoelectric patch where the voltage induced is also measured (output). Figure 4 presents the boundary conditions considered for the harmonic analyses. Therefore, for each damaged and undamaged structure, a complex elastance (V/Q, Volt/Coulomb) frequency response is measured for each piezoelectric patch. For each harmonic analysis, the inactive piezoelectric patch is kept in open-circuit electric boundary condition. The frequency range considered for the harmonic analyses is 0-50 kHz with a constant step of 10 Hz. Although it is well known that the structural damping could be affected by the delamination itself, for the sake of simplicity, a constant modal damping factor of 0.5% is assumed for all modes in this work.

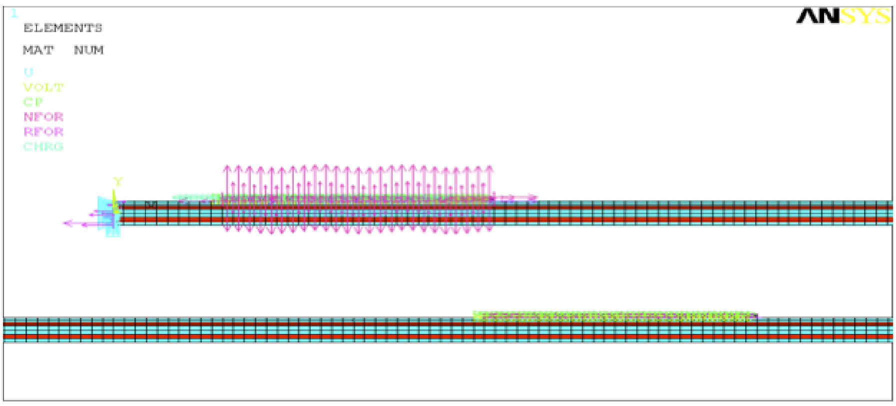

Figure 4. Boundary conditions considered for the harmonic analyses.

3. DEFINITION OF DAMAGE METRICS

This section presents the definition of some metrics that can be used for damage detection. They are divided into two groups: 1) metrics based on modal parameters, in particular the natural frequencies of the structure, and 2) metrics based on the frequency response of the structure, evaluated using electric impedance, admittance and elastance of piezoelectric patches bonded to the structure.

3.1 Metrics based on modal parameters

Several modal parameters may be used for the definition of metrics for damage detection, such as resonance or anti-resonance frequencies and mode shapes and their derivatives. Although the identification of such parameters normally requires the measurement of the response of the structure, they are set apart since they provide information about the structure at a particular frequency point.

In this work, only metrics based on resonance frequencies are considered. Although these are global parameters and, thus, should be less sensitive to local modifications of structural properties, such as small damages, they could be improved by repeated measurements using known local modifications, such as the electric boundary conditions of piezoelectric patches attached to the structure.

The first metric is defined as the relative difference between the resonance frequencies of the damaged structure and undamaged structure. The metric is improved by considering the electric boundary conditions of the two piezoelectric patches attached to the structure, such that

$$VRFN^{j}_{P1/P2} = 100|f^{jd}_{P1/P2} - f^{j}_{P1/P2}|/f^{j}_{P1/P2}, \tag{1}$$

where $f^{jd}_{P1/P2}$ is the j-th resonance frequency of the damaged structure, while $f^{j}_{P1/P2}$ is the one for the undamaged (reference) structure. The subscript $P1/P2$ represents the pair of electric boundary conditions of first and second piezoelectric patches, $P1 = \{SC, OC\}$ and $P2 = \{SC, OC\}$, and SC and OC stand, respectively, for short-circuit and open-circuit electric boundary conditions.

The second metric is based on the effective electromechanical coupling coefficient (EMCC) provided by a piezoelectric patch to the structure. The EMCC measures the fraction of vibratory energy stored in the structure that can be converted into electric energy by a given piezoelectric patch, due to the material electromechanical coupling. For the case where the structure vibrates in its j-th vibration mode, the EMCC of a piezoelectric patch can be defined as the relative difference between the squared resonance frequencies when the piezoelectric patch is in open-circuit and short-circuit electric boundary conditions (Trindade and Benjeddou, 2009). Therefore, the EMCC of the two piezoelectric patches bonded to the present composite structure are evaluated, respectively, as

$$EMCC^{j}_{P1} = 100\left(1 - f^{j\,2}_{SC/SC}/f^{j\,2}_{OC/SC}\right), \quad EMCC^{j}_{P2} = 100\left(1 - f^{j\,2}_{SC/SC}/f^{j\,2}_{SC/OC}\right). \tag{2}$$

A variation of the EMCC of each piezoelectric patch in the composite laminate structure, when compared to the EMCC of the same patch evaluated for the undamaged (reference) structure, can then be used as a damage metric, since a structural damage may affect the coupling between structure and each piezoelectric patch. Notice that a structural damage may either increase or decrease the EMCC of a given piezoelectric patch, that is the damage may either improve or deteriorate mechanical coupling between structure and patch and, thus, the EMCC of the piezoelectric patch. Thus, a metric is defined as the absolute difference between the EMCC of each patch evaluated for damaged and undamaged structures, such that

$$VEMCC^{j}_{P1} = |EMCC^{j}_{P1} - EMCC^{jd}_{P1}|, \quad VEMCC^{j}_{P2} = |EMCC^{j}_{P2} - EMCC^{jd}_{P2}|. \tag{3}$$

It could be expected that the closer the damage is to a given piezoelectric patch, the more the former would affect the EMCC of the latter.

Notice that both $VRFN$ and $VEMCC$ metrics provide one value for each resonance frequency and, thus, may lead to a quite large and hard to interpret database. Alternatively, average values of these metrics can be evaluated for given frequency ranges.

3.2 Metrics based on frequency response

While the metrics based on modal parameters presented previously measure the effect the damage may have at particular frequencies, metrics based on frequency response focus instead on the variation of the response over a given frequency range. This means that the response at all frequencies inside a given frequency range are accounted for. Evidently, this also means that too much information could be obtained making it difficult to store and draw conclusions. Instead, useful information can be obtained through averaged values over a given frequency range. Several metrics have been proposed in the literature to summarize the differences between the frequency responses measured for the damaged and undamaged structures, normally using an integral over the frequency range. On the other hand, there are several ways to measure the frequency response of a structure depending on input and output considered. The piezoelectric patches may be used as sensors and actuators, simultaneously, using impedance analyzers to measure the electric impedance of each piezoelectric patch. Starting from impedance measurements, several other complex measures may be evaluated, such as admittance and elastance, which can then be expressed using real and imaginary parts or amplitude and phase.

The damage metrics presented in this section can be divided in mainly two categories. Those that measure the relative difference between the responses of damaged and undamaged structures and those that measure the correlation between the two responses.

One of the most popular damage metrics is based on the Root Mean Square Deviation (RMSD) between the responses of damaged and undamaged structures. Sun *et al.* (1995) and Giurgiutiu and Rogers (1998) used the RMSD, evaluated from the real part of the impedance measured at piezoelectric patches, as a damage metric. However, the definition of RMSD provided in these works is different as for the position of the summation. Indeed, this leads to two damage metrics with different characteristics. They can be written as

$$RMSD_{Sun} = 100\sum_{i=1}^{n}\sqrt{(Z_i - Z_i^d)^2/(Z_i)^2}, \tag{4}$$

$$RMSD_{GR} = 100\sqrt{\sum_{i=1}^{n}(Z_i - Z_i^d)^2/\sum_{i=1}^{n}(Z_i)^2}, \tag{5}$$

where Z_i and Z_i^d represent one component (real part, imaginary part, amplitude,...) of the complex frequency responses (impedance, admittance, elastance,...) of the undamaged and damaged structures, respectively, evaluated at i-th frequency point.

Another similar damage metric can be defined based on the first order relative difference between the responses of damaged and undamaged structures. The Mean Absolute Percentage Deviation (MAPD) metric is evaluated by the summation of the absolute deviations of the responses at each frequency point, relative to the responses of undamaged structure, such that (Tseng and Naidu, 2002)

$$MAPD = (100/N)\sum_{i=1}^{n}\left|(Z_i - Z_i^d)/Z_i\right|, \tag{6}$$

where N is the number of frequency points considered in the frequency range.

p-norms, such as maximum (infinity) and euclidian (quadratic) norms, could also be used to measure the distances between the responses of damaged and undamaged structures. The generic p-norm of a component of the frequency response of the structure can be defined as

$$\|Z\|_p = \left(\sum_{i=1}^{n}|Z_i|^p\right)^{(1/p)}, \tag{7}$$

and, thus, a damage metric could be defined as the relative difference between the maximum and euclidean norms of the frequency responses of the damaged and undamaged structures, such that (Bueno *et al.*, 2006)

$$H_{inf} = 1 - (\|Z^d\|_\infty)^2/(\|Z\|_\infty)^2, \tag{8}$$

$$H_2 = 1 - (\|Z^d\|_2)^2/(\|Z\|_2)^2, \tag{9}$$

where $\|Z^d\|_\infty$, $\|Z^d\|_2$, $\|Z\|_\infty$ and $\|Z\|_2$ are the maximum and euclidean norms of a given component of the frequency responses of the damaged and undamaged structures, respectively.

On the other hand, damage metrics could be also based on the correlation between the frequency responses of damaged and undamaged structures, instead of considering their differences. While for difference-based metrics, the higher the difference the stronger the damage (in theory at least), in the case of correlation-based metrics, the higher the correlation the smaller the damage. Several correlation-based damage metrics have been proposed in the literature. The Correlation Coefficient Deviation (CCD) measures the relation between the frequency responses of damaged and undamaged structures. Zagrai and Giurgiutiu (2001) used the CCD damage metric, defined in the following forms,

$$CCD = 1 - (1/\sigma_Z\sigma_{Z^d})\sum_{i=1}^{n}(Z_i - \bar{Z})(Z_i^d - \bar{Z}^d), \tag{10}$$

$$CCD3 = \left[1 - (1/\sigma_Z\sigma_{Z^d})\sum_{i=1}^{n}(Z_i - \bar{Z})(Z_i^d - \bar{Z}^d)\right]^3, \tag{11}$$

where Z_i and Z_i^d represent a component of the frequency responses of undamaged and damaged structures, respectively. $\bar{Z}$ and σ_Z, and $\bar{Z}^d$ and σ_{Z^d}, are the corresponding mean values and standard deviations.

Another damage metric could be defined in terms of the covariance of the damaged and undamaged frequency responses,

$$COV = (1/N)\sum_{i=1}^{n}(Z_i - \bar{Z})(Z_i^d - \bar{Z}^d). \qquad (12)$$

4. RESULTS AND DISCUSSION

This section presents the results of damage metrics based on modal parameters and frequency response evaluated for the cantilever laminate beam. Figure 5 shows the variation of resonance frequencies when the length and position of the delamination is varied. The results are only shown for both piezoelectric patches in short-circuit, since for other electric boundary conditions similar results were found. In Figure 5a, a delamination with length 30 mm and located at 60 mm from the clamped end was considered. Similar results were found for the other delaminations. It can be observed that this damage metric may be effective to evaluate the growth of the delamination but is not sensitive to the damage location (Figure 5b). Alternatively, the variation of resonance frequencies can be averaged over a given frequency range to compact the information. Figure 6 presents the mean variation for vibration modes 1-25, 26-50, 51-75 and 76-100. It shows that the group of vibration modes 26-50 seems more sensitive to delamination, however in all ranges the growth of delamination length increases the damage metric.

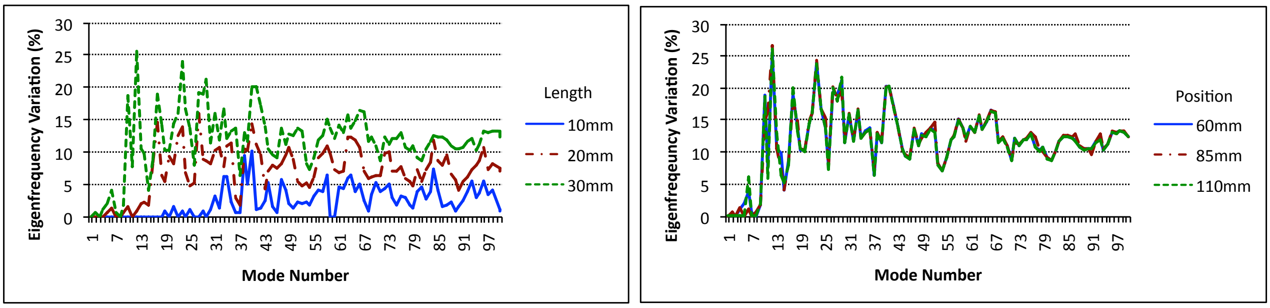

Figure 5. Damage metric based on the variation of resonance frequencies for varying length and position of delamination.

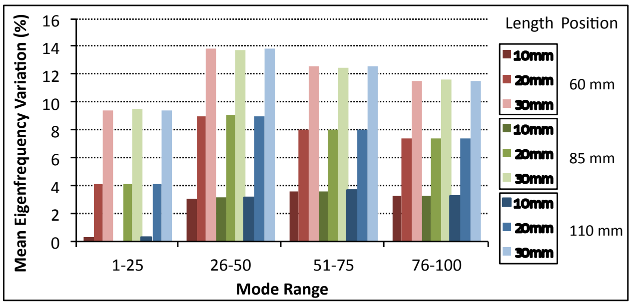

Figure 6. Mean variation of resonance frequencies for varying length and position of delamination.

Figure 7 shows the variation of EMCC of the two piezoelectric patches for a delamination with length 30 mm and located at 60 mm from the clamped end. It can be seen that the delamination affects the EMCC of only a few vibration modes. Although the delamination seems to affect more the EMCC of the first piezoelectric patch, this is not related to the proximity of the delamination to this patch since the same behavior was also observed for delaminations closer to the second patch. As for the variation of resonance frequencies, the variation of EMCC may be averaged to simplify the analysis. Figures 7b and 7c show the mean variation of EMCC of first and second piezoelectric patches, respectively, for vibration modes 1-25, 26-50, 51-75 and 76-100. They confirm that the vibration modes 26-50 are more sensitive to the delamination. However, unlike the variation of resonance frequencies, the variation of EMCC does not increase monothonically with the increase of delamination length.

For the evaluation of damage metrics based on frequency response, the complex elastance obtained from ANSYS was post-processed in MATLAB to obtain the real part, imaginary part and amplitude of elastance $E^*(\omega)$, impedance $Z^*(\omega) = E^*(\omega)/(i\omega)$ and admittance $Y^*(\omega) = (i\omega)/E^*(\omega)$. Figure 8 presents the real part of complex impedance, admittance and elastance evaluated for undamaged and damaged structures over the frequency range 0-50 kHz. For this example, a delamination of length 30 mm and located at 60 mm from the clamped end is considered. It is noticeable that

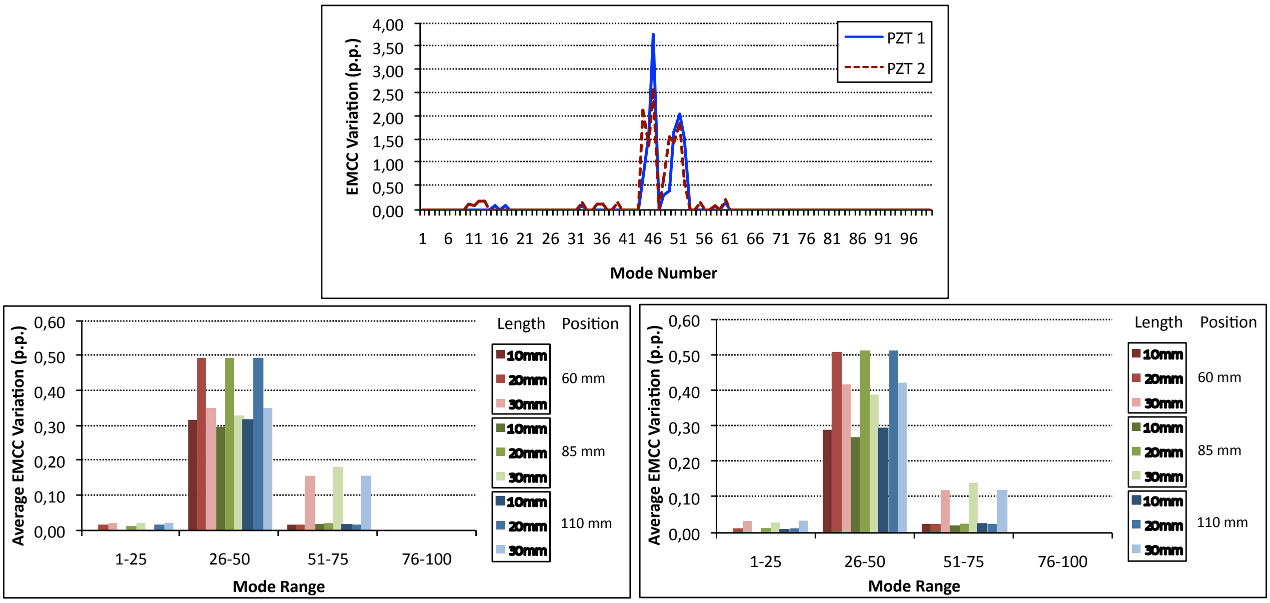

Figure 7. Damage metric based on the variation of EMCC for varying length and position of delamination.

the delamination does induce a change in the frequency response, however it is not easy to understand the effect of the delamination on the response frequency by frequency. Instead, the damage metrics proposed in the previous sections are used to provide scalar metrics that could be easier to interpret.

Besides, previous studies suggest that it is adviseable to analyze tighter frequency ranges. Therefore, the frequency range 0-50 kHz was divided into five tighter frequency ranges: 0-10 kHz, 10-20 kHz, 20-30 kHz, 30-40 kHz and 40-50 kHz. This may increase the sensitivity of the damage metrics but it also increases the number of analyses to be performed. Indeed, this leads to 6480 cases to be analyzed, consisting of 3 quantities, 3 components, 8 metrics, 5 frequency ranges, 2 piezoelectric patches, 3 delamination lengths and 3 delamination positions. Therefore, two performance criteria were defined to filter the cases of interest and find the combinations that are capable of identifying the growth and location of the delamination. The first criterion is defined as follows: the damage metric should grow monothonically with the increase of delamination length. The second criterion reads: for the three delamination length values, the damage metric measured by a given piezoelectric patch should increase if the delamination approaches the patch.

The first important result obtained by this analysis is that only few combinations of quantities, components, metrics and frequency ranges fully respect the first or the second criterion. None of the combinations fully respect the two criteria simultaneously.

Analysis of the first criterion alone has shown that the most appropriate frequency range is the lowest one, 0-10 kHz, and the most appropriate damage metrics are those based on relative difference, H2 and RMSD(GR), using either imaginary or real parts of the impedance. Figure 9 presents the results for the most appropriate damage metrics to identify delamination length, compared to the ideal behavior expected for a damage metric.

In a second, and more complex, study, the second criterion was analyzed alone. There were a number of combinations that respected this criterion, that is the damage metric measured by a given piezoelectric patch increases when the delamination is closer to it. However, as the position of the damage is unknown, for most practical cases, the second criterion was enhanced by defining that the damage metric measured by the two piezoelectric patches should be equal (at a precision of $\pm 10\%$ when the damage is at the second position (85 mm from the clamped end) that is equidistant from the two patches and that the ratio between the damage metrics measured by the two piezoelectric patches should be approximately inversely equal at the two extreme positions. For instance, if the damage metric measured by the first patch is two times the one measured by the second patch when the delamination is in the first position (closer to first patch), then the damage metric measured by the first patch should be approximately half the one measured by the second patch when the delamination is in the third position (closer to the second patch).

Analysis of the refined second criterion alone has shown that the most appropriate frequency range is a higher one, 30-40 kHz, and the most appropriate damage metric is the one based on the relative difference of H_2 norms, evaluated from the real part or amplitude of elastance and imaginary parts of impedance and admittance. Figure 10 presents the results for the most appropriate damage metrics to identify delamination position, compared to the ideal behavior expected for a damage metric.

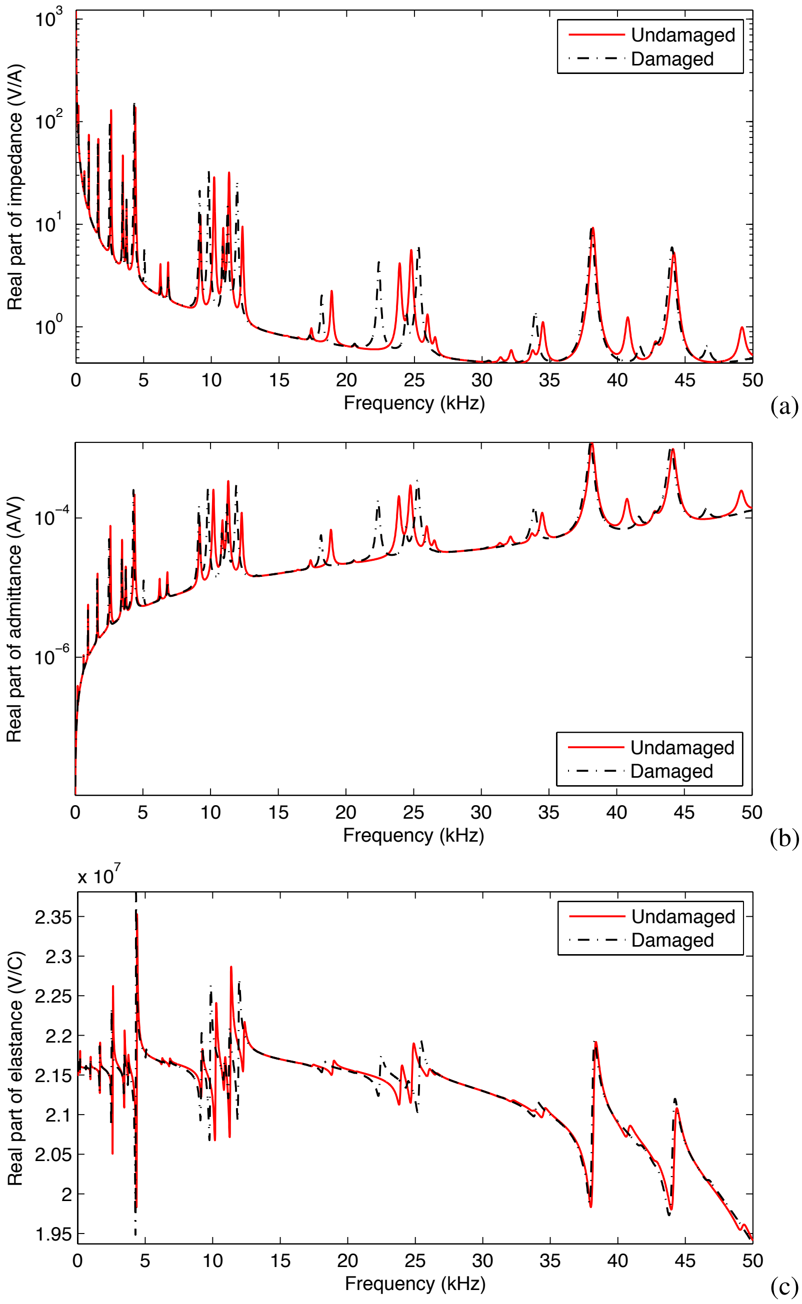

Figure 8. Real part of impedance (a), admittance (b) and elastance (c) for damaged and undamaged structures.

5. CONCLUSIONS

This work presented an analysis of different techniques for the detection of position and size of a delamination in a composite structure using piezoelectric patches, with the aid of a 2D ANSYS finite element model. Several metrics and techniques were evaluated in terms of their capability of identifying, with relative accuracy, the presence, location and severity of the damage. Results show that both modal and impedance-based techniques are able to identify the presence of the delamination-type damages, provided the piezoelectric patches are close enough to the damage. It is also shown that impedance-based techniques seem more effective than modal ones for the detection of delamination position and size. Future works should be directed to the improvement of the computational model.

6. ACKNOWLEDGEMENTS

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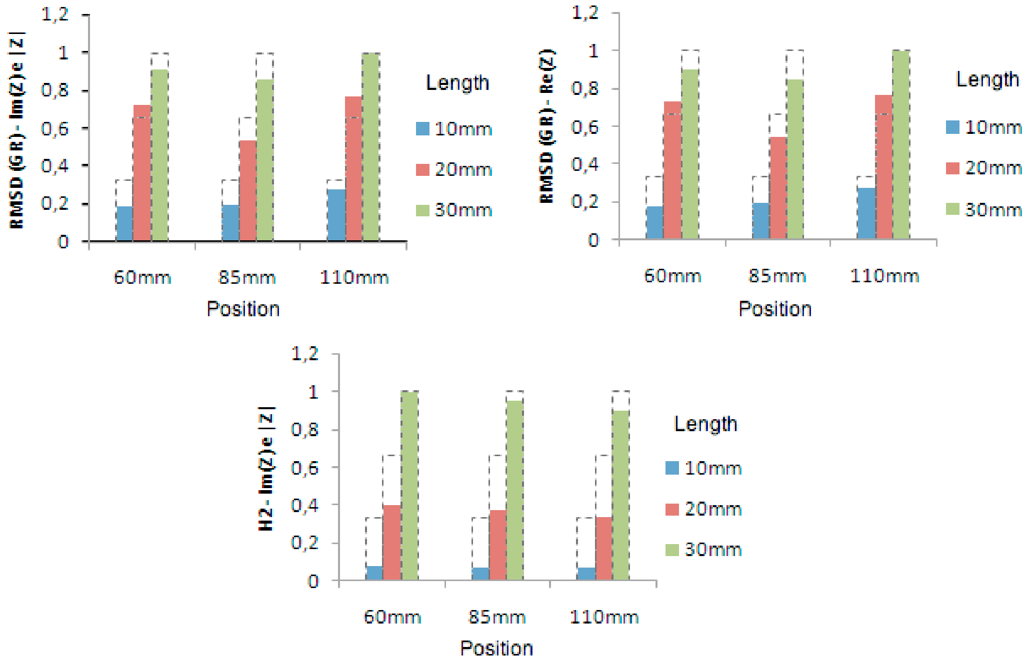

Figure 9. Results for the most appropriate damage metrics to identify delamination length.

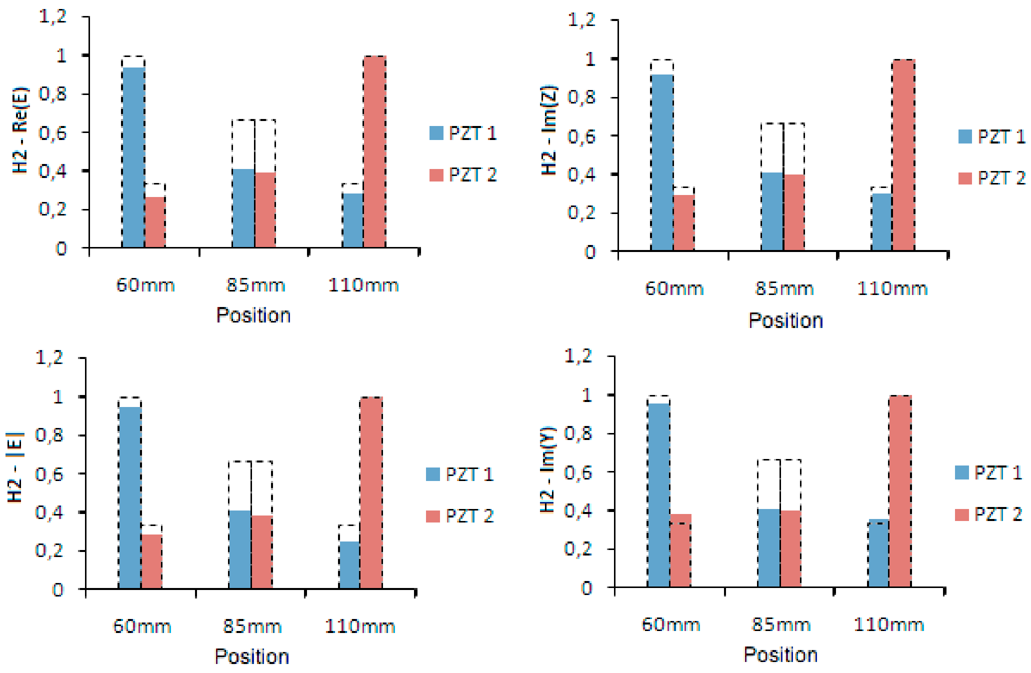

Figure 10. Results for the most appropriate damage metrics to identify delamination position.

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8. Responsibility notice

The authors are the only responsible for the printed material included in this paper.