Characterization of Delamination by Using Damage Indices

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ABSTRACT: A damage index based on in-plane modal strain is developed to characterize the dynamic behavior of laminated composite plates of arbitrary thickness with discrete multiple delaminations. A recently developed improved layerwise laminate theory is used to accurately describe the displacement field and capture the transverse shear effects for the moderately thick plates. The multiple seeded delaminations are modeled using Heaviside step functions. The performance of the damage index is compared to previously developed damage indices. Numerical results indicate that the newly developed damage index is able to identify the location and the extent of delamination more accurately and more consistently, compared to other indices, in plates with small discrete multiple delaminations. Experiments using a Scanning Laser Doppler Vibrometer (SLDV) and strain gauges are conducted and the results obtained agree well with the numerical results.

KEY WORDS: damage characterization, strain-based damage index, composite laminates, multiple seeded delaminations, improved layerwise theory, laser scanning vibrometry.

INTRODUCTION

COMPOSITE MATERIALS CONTINUE to have a positive impact on the aerospace industry due to their high strength to weight ratio and stiffness tailoring characteristics. In the presence of defects, such as delamination or matrix cracks, these benefits can be compromised by severe reductions in the load carrying capability. Early detection of damage is therefore, very critical in understanding the structural integrity of composite structures. Experimental damage detection techniques include localization by utilizing acoustic, ultrasonic, magnetic field, X-ray, or thermal principles. These techniques require knowledge of and access to the damage zone. In addition, these methods can be time

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consuming and expensive. The development of a robust health monitoring procedure requires an in-depth understanding of the structural behavior at the onset of damage. An essential tool for understanding the effects of damage parameters on the structural response is an analysis procedure, which is both accurate and cost-effective. In the last few years, there has been extensive work on the modeling of composite structures. In this work, only vibration-based characterization studies are discussed and some relevant research that has led to the advancement of the current topic is discussed in the following section.

Timoshenko beam theory was used by Shen and Grady [1] to discuss the free vibration characteristics of a delaminated composite beam. Doebling et al. [2] published an exhaustive review of damage detection methods based on the vibrational characteristics. The vibrational characteristics of a structure have also been extended to develop damage indicators to predict the presence of defects. Yuen [3] has shown that the normalized changes in the fundamental mode shapes of a cantilever plate model has definitive characteristics, which can be related to the location and extent of damage. He has shown that the modal displacements in a damaged cantilever plate changes slope near the damaged zone. The curvature mode shapes are used in an investigation by Pandey et al. [4] as a method of identifying the location of damage. They developed a damage indicator based on the absolute difference in the curvature mode shapes between a healthy and a damaged beam. This approach proved to locate damage better than the absolute difference in the displacement mode shapes. Ratcliffe and Bagaria [5] extended Pandey's work by locally smoothing the curvature and formulating the gapped smoothing technique. This formulation eliminated the use of a healthy reference. Harris [6] established a method of damage identification using a modal consistency vector. The formulation creates a scalar constant that measures the equivalence between a given modal vector and a reference modal vector. The scalar quantity is called the modal assurance criterion (MAC). Complimentary to the MAC is the coordinated modal assurance criterion (COMAC). This formulation is used to identify which degrees of freedom (DOF) have the largest influence on a low value of MAC. Chattopadhyay and Dragomir-Daeseu later observed that modal strain is a more appropriate measure of identifying the presence of delamination than classical mode shapes. They proposed strain-based damage indices and modified versions of the MAC and the COMAC, the modal strain assurance criterion (MSAC) and the coordinated modal strain assurance criterion (COMSAC) [7].

Damage detection models are usually simulated using simple structures with a small number of DOFs. Relatively less amount of work has been reported on damage detection in composite structures. This is primarily due to the complexities associated with the composite anisotropy and distributed damage. Damage detection is an inverse problem; therefore prior to developing a robust detection procedure for composite structures, it is necessary to understand the effects of damage on the structural response. The goal of this research is to develop an integrated vibrational approach combining accurate analysis techniques and experiments to characterize the presence of damage in composite plates. A previously developed strain-based damage index is further modified and extended to detect the location and extent of seed multiple damage in composite plates. The results are compared with those obtained using MSAC and COMSAC. Experiments using a Scanning Laser Doppler Vibrometer (SLDV) and strain gauges are also conducted to validate the results obtained from simulations.

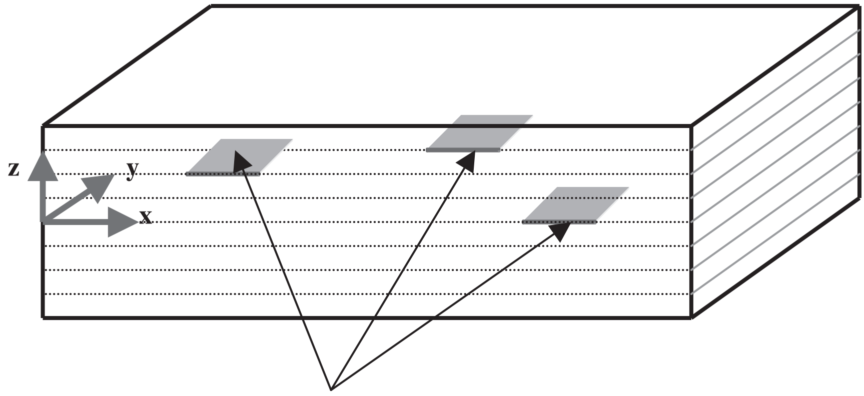

Figure 1. *Schematic of a cantilever plate with embedded multiple discrete delaminations.*

THEORY

Displacement Field Description

Composite plates of moderately thick construction in the presence of seeded discrete delaminations are considered (Figure 1). In such cases, transverse shear stresses are important. Therefore, an improved layerwise theory capable of accurately and efficiently predicting these stresses and capturing the kinematics of discrete delaminations is used [8]. In this theory, the in-plane displacement field of the perfectly bonded layers (healthy) is modeled using a zigzag-like deformation. To address the overall response of the laminate, a first-order shear deformation theory is used. The theory uses layerwise functions to accommodate the complexity of the zigzag in-plane deformation. To model multiple discrete delaminations, the displacement field is supplemented with Heaviside unit step functions, which introduce independent displacement fields above and below the delamination. The displacement field of a point with the coordinates (x, y, z) is described as follows:

$$U_i^L(x,y,z) = u_i(x,y) + \phi_i(x,y)z + \theta_i^L + \psi_i^L(x,y)h(z) + \sum_{j=1}^{N-1} \overline{u}_i^j(x,y)H(z-z_j) \qquad (1)$$

where the superscript k denotes the kth layer of the laminate and subscript i represents the x or y coordinate. The displacements of the reference plane denoted by u_i and ϕ_i represent rotations of the normal to the reference plane. The layerwise structural unknowns defined for each laminate are θ_i^k and ψ_i^k. To consider possible slipping and separation between sublaminates, the term $\overline{u}$ is added at the delaminated interfaces (z_j). The term $H(z-z_j)$ is the Heaviside unit step function. The theory satisfies traction-free boundary conditions at all free surfaces. Interlaminar shear stress continuity and displacement continuity are enforced to reduce the total number of unknowns, thereby ensuing computational efficiency [9].

DAMAGE INDEX FORMULATION

It is easier to measure strain using a variety of techniques compared to modal displacements. Damage identification methods based on modal strains have recently been addressed by Chattopadhyay and Dragomir-Daescu [7] and are further investigated in this work. In the previously reported work, strain-based damage indices were developed using only single in-plane modal strains for three modes of vibration, and the displacement field was modeled using a higher-order theory [10]. The damage index was used to detect through-the-width delaminations of sizes larger than 10% of the plate length. It must be noted that although higher-order-based theories are capable of predicting the through-the-thickness transverse shear stresses, they fail to provide ply-level information that are critical to delamination. In this work, as noted before, the displacement field information is modeled using an improved layerwise theory [8], which satisfies stress and displacement continuities at ply interfaces as well as traction-free boundary conditions at all free surfaces (including delaminated surfaces). Also, the theory is used to model discrete seeded delaminations. Therefore, the performance of the developed damage index is demonstrated in quantifying the existence and extent of multiple discrete delaminations.

The new strain-based damage index calculates the normalized difference between the modal strains of the healthy reference and the damaged structure for each DOF in the structure. These differences are squared to reduce the presence of noise and enhance the differences. The sum of the squares is normalized so that a value less than one signals the presence of damage. The normalization further magnifies the differences between the healthy and the damaged plates. The location of the damage is indicated by the DOF with the largest value of the damage index. The formulation also includes several modes of vibration as well as both in-plane displacement directions. The formulation of the new strain-based damage index is as follows:

$$\delta_m = \frac{\sum_{k=1}^{N} \left[\varepsilon_m^{rk} - (\varepsilon_m^{rk})_{\mathrm{del}}\right]^2}{\left[\sum_{k=1}^{N} \left(\varepsilon_m^{rk}\right)^2 + \sum_{k=1}^{N} \left(\varepsilon_m^{rk}\right)_{\mathrm{del}}^2\right]} \tag{2}$$

The performance of this damage index is compared to MSAC and COMSAC. These indices are described next for the sake of clarity.

The MSAC is a measure of the modal consistency between a given vector and a reference vector. In this investigation the given vector is the modal strain of a damaged plate and the reference vector is the modal strain of the corresponding healthy plate. Thus, MSAC assumes the following form:

$$MSAC_k = \frac{\sum_{m=1}^{M} \left[\left(\varepsilon_m^{rk}\right)\left(\varepsilon_m^{rk}\right)_{\mathrm{del}}\right]^2}{\left(\sum_{m=1}^{M} \left(\varepsilon_m^{rk}\right)^2\right)\left(\sum_{m=1}^{M} \left(\varepsilon_m^{rk}\right)_{\mathrm{del}}^2\right)} \tag{3}$$

In Equation (2), the summation is extended over the entire plate for healthy and delaminated in-plane modal strains. The subscript "del" is used to represent the delaminated structure. The "ε_m^{rk}" term is the modal strain of the kth mode of vibration in the r coordinate direction for the mth DOF. It must be noted that MSAC is a comparison between two vectors and has values between 0 (no correlation) and 1 (complete correlation). The COMSAC identifies the DOF of the greatest influence to the low MSAC number. Thus COMSAC is the summation over several modes of vibration. In a given location m, the strains for the healthy and delaminated plates are paired for the kth mode of vibration. All N modal healthy and delaminated strain pairs in the m locations are added. This calculation produces a COMSAC value in the m location of the plate. The formulation for the COMSAC is as follows:

$$\mathrm{COMSAC}_m = \frac{\sum_{k=1}^{N}\left[\left(\varepsilon_m^{rk}\right)\left(\varepsilon_m^{rk}\right)_{\mathrm{del}}\right]^2}{\left(\sum_{k=1}^{N}\left(\varepsilon_m^{rk}\right)\right)^2\left(\sum_{k=1}^{N}\left(\varepsilon_m^{rk}\right)_{del}\right)^2} \tag{4}$$

Contrary to the MSAC, low values of the COMSAC indicate close correspondence between the healthy and delaminated plates in the m location. Graphing the COMSAC over the domain of the structure identifies the location (if any) of difference between the healthy and delaminated plates.

RESULTS

The newly developed damage index is used to detect the seeded delaminations in thick composite plates of various ply-stacking sequence. The results are compared with those obtained using MSAC and COMSAC. The dynamic response of composite plates is simulated using a finite element algorithm based on an improved layerwise theory [8]. The simulations are verified experimentally using strain gauges and SLDV. Plates with both single and multiple discrete delaminations are considered. The possible locations of the delaminations (in-plane and through-the-thickness) are shown in Figure 2. All composite

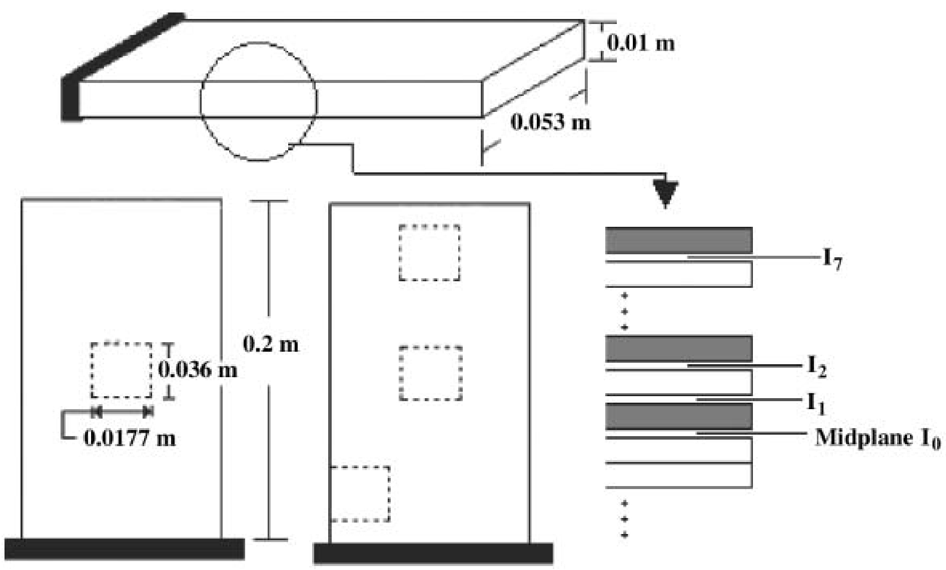

Figure 2. *A cantilever plate model with in-plane location of multiple delaminations.*

Table 1. MSAC values for simulated composite plates.

Stacking sequence	Number of delaminations	Mode of vibration	MSAC value
0/90	1	1	0.006
		2	0.009
		3	0.004
+45/−45	1	1	0.014
		2	0.010
		3	0.011
0/90	3	1	0.052
		2	0.035
		3	0.039

plates considered in this investigation contain 16 plies and the interface identification is detailed in Figure 2.

SIMULATION RESULTS

In the numerical analysis, cantilever plates are modeled with $[0/90]_{4s}$ and $[+45/-45]_{4s}$ stacking sequences. Each plate is 0.2 m long, 0.053 m wide and 0.01 m thick. The material considered in this investigation is carbon cyanate ($E_1 = 372$ GPa, $E_2 = 4.12$ GPa, $G_{12} = 3.99$ GPa, $\rho = 1788.5\ \mathrm{kg/m^3}$, $\nu_{12} = 0.275$, and $\nu_{23} = 0.42$). The size of each discrete rectangular delamination is $0.036 \times 0.0177\ \mathrm{m^2}$. The in-plane modal displacement field information, obtained from the finite element solution, is used to calculate the in-plane modal strains, which are then used to compute the damage indices. The MSAC values for the centrally located delaminated plates are shown in Table 1 for the two stacking sequences. As seen from Table 1, MSAC values are small (< 6%) for the two models in all the three vibrational modes considered. The low MSAC values indicate an inconsistency between the healthy and the delaminated plates and signals the existence of damage. However, these values alone are not enough to predict the location and the extent of the delaminations.

The COMSAC and δ_m damage indices are calculated for a single delamination case. The results for composite plates with the $[0/90]_{4s}$ and $[+45/-45]_{4s}$ stacking sequence are shown in Figure 3. In both cases the δ_m and COMSAC damage indices are able to predict the delaminated areas by displaying large peaks in the graphs. In both plate models the COMSAC shows additional smaller peaks outside the damaged zone. Thus, COMSAC overpredicts the extent of the delaminated zones in these plates. It must be noted that the formulation of the COMSAC (Equation (3)) produces a fourth-order polynomial in the denominator. Any interpolation or round-off error that is generated in the computational analysis is therefore magnified due to the presence of these terms. This may explain the additional peaks in areas where there is no damage. The increased anisotropy present in the $[+45/-45]_{4s}$ composite plate generates more computational noise when considering several modes of vibration. Consequently, the overprediction in the COMSAC result is more extensive in the plate with $\pm 45°$ fiber orientations. Contrary to COMSAC, the δ_m formulation only consists of second-order terms. As a result, the δ_m damage index clearly identifies the extent of delamination in both cases.

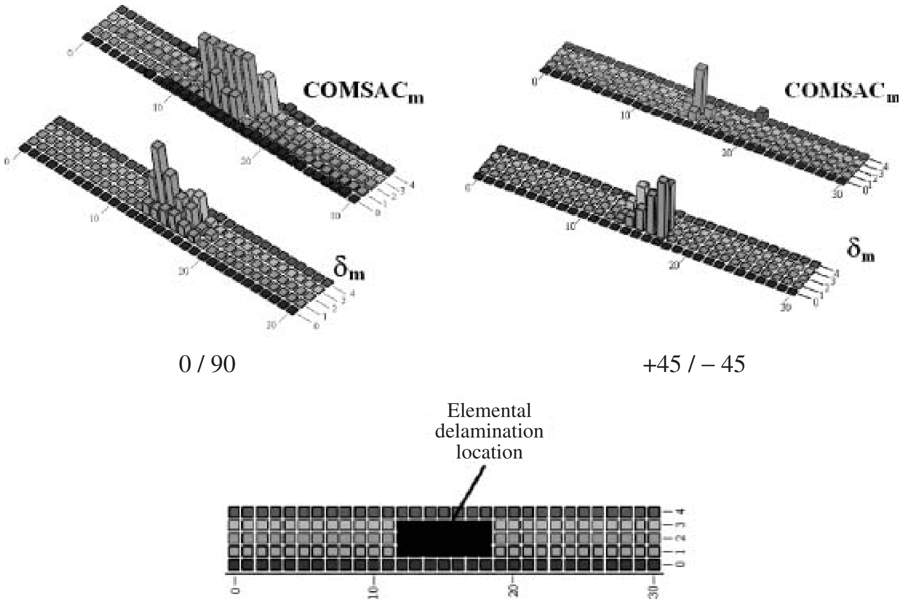

Figure 3. *Damage indices for the cantilever plate with a single discrete delamination.*

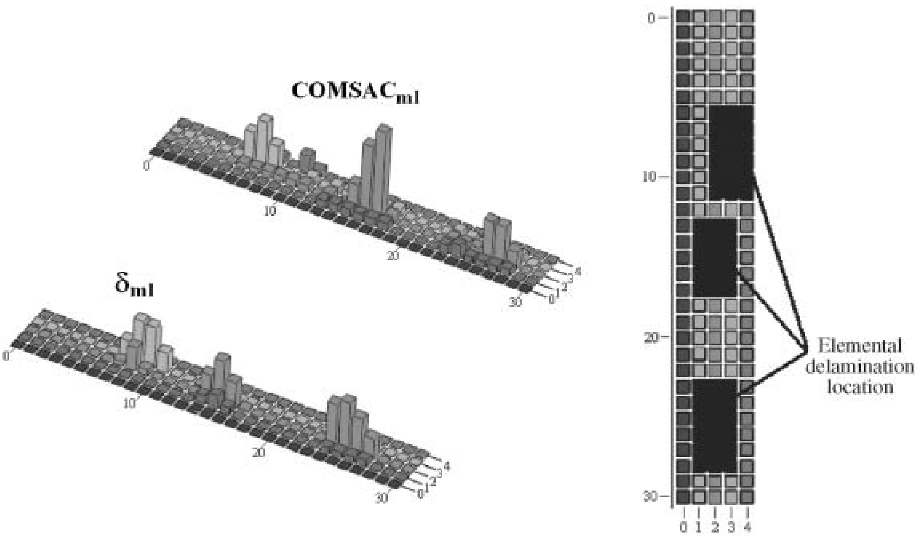

Figure 4. *Damage indices for the cantilever plate with three discrete delaminations for [0/90]$_{4s}$ stacking sequence.*

Next simulations are conducted on a composite plate with three delaminations, as shown in Figure 4, and $[0/90]_{4s}$ stacking sequence. The MSAC values shown in Table 1 indicate the presence of damage with values less than 6%. The COMSAC and δ_m damage index results are shown in Figure 4 for the multiple delamination plate. The COMSAC and δ_m predict the location of the delamination by displaying peaks in the damage areas. The graph of COMSAC once again shows smaller peaks outside the damaged zone, thus overpredicting the extent of delamination. Similar to the single discrete delamination case,

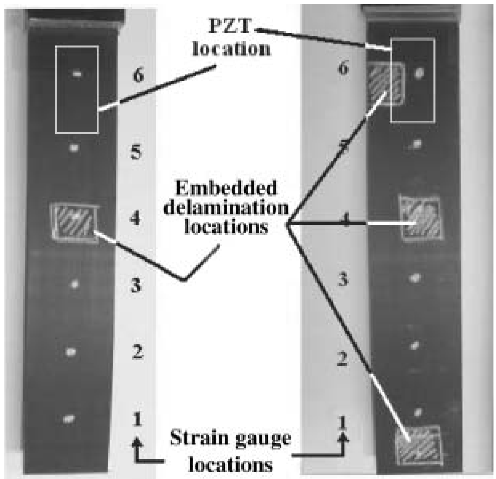

Figure 5. *Experimental composite plate models for one delamination and multiple discrete delaminations.*

δ_m displays peaks only in the delaminated areas. Thus δ_m is capable of identifying the location and extent of delamination more accurately in both single and multiple delamination cases.

Experimental Results

The simulation models establish a baseline to further investigate the effectiveness of the damage indices in predicting delamination using experimentally captured modal displacements and strains. Composite plates are manufactured with 16 carbon cyanate laminates. Two stacking sequences, ($[0/90]_{4s}$ and $[45/-45]_{4s}$), and two interface locations (I_2 and I_7, Figure 1) for delaminations are considered in this experimental study. The delamination is introduced by embedding a Mylar film ($0.036 \times 0.0177\,m^2$) at the locations shown in Figure 2.

Strain gauges are attached to one side of the plate at six locations, approximately 1 in. apart, along the length of the plate (Figure 5). The strain gauge locations are numbered 1–6 (Position 1 being at the free end of the plate). A piezoelectric actuator is used to generate a sinusoidal pulse at different frequencies. The actuator is attached on the back surface of the plate slightly above the clamped end. As the plate vibrates from the actuator pulse, the voltage from the strain gauges is converted to modal strains using a Labview interface program. These modal strains are used to calculate the damage indices. The MSAC results are shown in Table 2, and the δ_m and COMSAC results are shown in Figure 6.

As seen from Table 2, the MSAC values are close to unity ($>87\%$) for all four plates. These values indicate a close correspondence between the healthy and the delaminated plates, not signaling the presence of damage. Figure 6 shows the δ_m and COMSAC results for the plates with centrally located delamination for the two stacking sequences. The δ_m displays multiple peaks along the length of the plate, the largest peak being at the delamination location for both I_2 and I_7 interface locations. The COMSAC results show multiple peaks of relatively the same height; therefore these results do not clearly identify the delamination locations. Thus, the MSAC and COMSAC show no significant difference between the healthy reference and the delaminated plates.

Table 2. MSAC values for experimental composite plates with single discrete delamination.

Stacking sequence	Delamination layer	Number of delamination	Mode of vibration	MSAC value
0/90	I_2	1	1	0.890
			2	1.000
			3	0.980
			4	0.870
	I_7	1	1	1.000
			2	0.990
			3	1.000
			4	1.000
+45/−45	I_2	1	1	1.000
			2	0.999
			3	0.995
			4	0.988
	I_7	1	1	0.840
			2	0.996
			3	0.998
			4	1.00

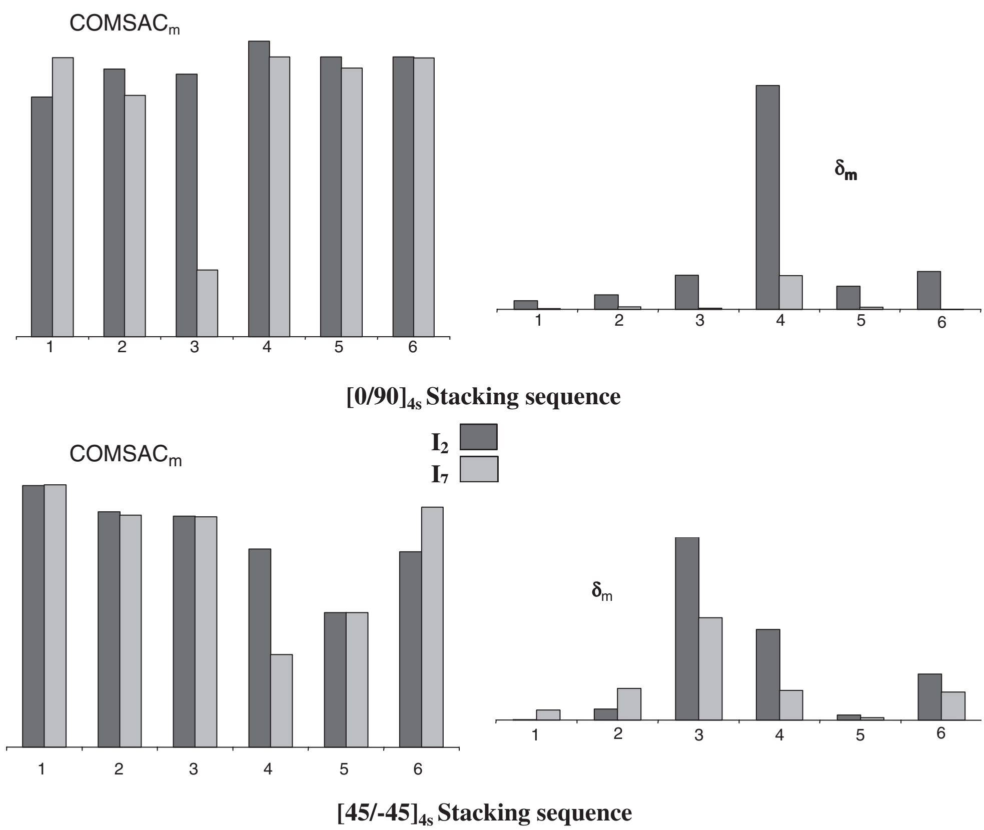

Figure 6. *Comparison of damage indices for a single centrally located delamination.*

These differences in the results, between the experiment and simulation, can be explained as follows. In the simulated plate models 155 nodal points are used to calculate the modal strain for a given composite plate model. In contrary, during experiments, the modal strains are measured using the strain gages located at six distinct locations. Thus, the number of measured points on the experimental model is not enough to calculate a difference in the modal strain between the healthy and the delaminated plates. Thus, experimentally, the MSAC and COMSAC fail to identify the existence of delaminations. The δ_m formulation is based on the square of the absolute difference between modal strains of the healthy and delaminated plates, which magnifies the differences in the modal strains. Therefore, this damage index still provides information on the existence of delamination. This further illustrates the robustness of this simple formulation.

This observation is also true for the plates with multiple delaminations, as shown in Table 3 and Figure 7. Figure 7 shows the δ_m and COMSAC results for the laminated plates with multiple delaminations. The graph of δ_m shows multiple peaks along the length of the plate with the larger peaks near the delaminated areas. The COMSAC does not clearly identify the delaminated area. Likewise, the corresponding MSAC values for these laminated plates range from 0.989 to 0.997, indicating close correspondence (or absence of damage) with the healthy reference. The δ_m damage index is able to identify the delaminated regions in plates with both $[0/90]_{4s}$ and $[45/-45]_{4s}$ stacking sequence.

The δ_m results presented in Figure 6 compare delamination locations through the thickness (I_2 and I_7). The peaks are large in the delaminated region for locations closer to the midplane (I_2). When delamination is closer to the free surface of the plate (I_7), the stiffness of the delaminated plate is comparable to the stiffness of the healthy plate. Therefore, the difference in modal strains of the healthy and damaged plate is small. Thus, the closer the delamination location is to the midplane, the easier it is to detect its existence and extent using the δ_m damage index.

Table 3. MSAC values for experimental composite plates multiple delaminations.

Stacking sequence	Delamination layer	Number of delamination	Mode of vibration	MSAC value
0/90	I_2	3	1	0.998
			2	0.998
			3	0.988
			4	0.993
	I_7	3	1	0.998
			2	0.997
			3	0.993
			4	0.996
+45/−45	I_2	3	1	0.996
			2	0.997
			3	0.992
			4	0.995
	I_7	3	1	0.993
			2	0.997
			3	0.989
			4	0.994

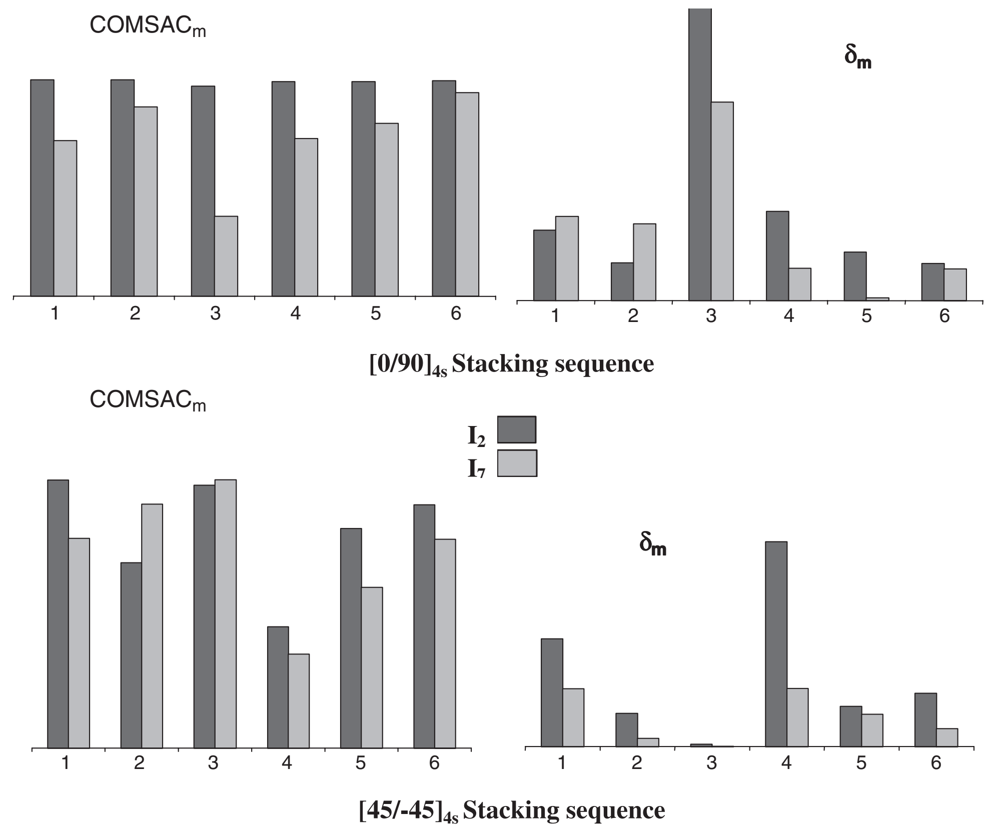

Figure 7. Comparison of damage indices for multiple delaminations.

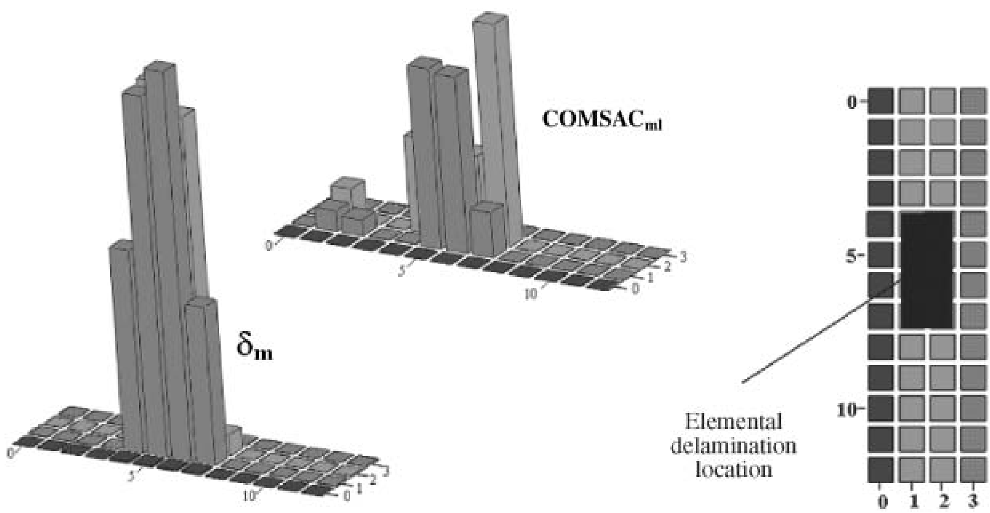

Figure 8. Comparison of damage indices for a single centrally located delamination using out-of-plane modal strains.

In the experimental results presented, only in-plane strains measured using strain gauges have been used in the formulation of the damage index. To obtain the out-of-plane measurements, the SLDV is used [11]. The out-of-plane modal displacements for a plate with a single I_2 delamination and $[0/90]_{4s}$ stacking sequence are measured. The modal displacements of five modes of vibration are used to calculate the out-of-plane modal strains. The δ_m and COMSAC damage indices are then formulated using only the out-of-plane modal strains generated by the SLDV. The two damage indices are compared in Figure 8. As seen from this figure, both δ_m and COMSAC are able to predict the delamination location by displaying large peaks in the damage zone. However, the COMSAC still shows additional peaks outside the delamination area. The presence of these additional peaks can be explained as follows. The COMSAC formulation consists of a fourth-order polynomial in the denominator. Therefore, any experimental noise associated with the SLDV measurements gets magnified resulting in computational noise, which introduces the additional peaks. The simplicity of the δ_m damage index formulation leads to clear identification of the location and extent of delamination for out-of-plane modal strains, also.

CONCLUSION

An investigation is conducted using a combination of refined analysis and experiments to characterize the presence of seeded delamination in laminated composite structures. Plates of various stacking sequences and multiple delaminations are studied. A recently developed analysis technique, based on an improved layerwise theory, is used in the numerical investigation. Experiments are conducted using Scanning Laser Doppler Vibrometer, piezoelectric actuator, and strain gauges to capture the modal strain information. The success of a strain-based damage index (δ_m) in detecting the presence and extent of delamination is investigated. Comparisons are made with two other damage indices, MSAC and COMSAC. It is seen that COMSAC fails to predict the extent of damage even for moderately sized delaminations. Experimentally it is observed that COMSAC and MSAC fail to predict damage for cases with small delaminations, where small strain changes occur between the healthy and the damaged plates. The COMSAC and MSAC also fail to predict the damage location for composite plates where the modal strain is measured at a small number of locations. The strain-based damage index provides more accurate information on the damage location and extent, in all of the cases studied.

NOMENCLATURE

x, y, z = in-plane and out-of-plane coordinate directions
L = laminate layer
U_i^L = in-plane displacement field, where $i = x, y$
Ui = in-plane displacement field at the reference surface, where $i = x, y$
$\phi_i, \psi_i^L, \theta_i^L$ = structural unknowns, where $i = x, y$
$h(z)$ = through-the-thickness function
H = laminate thickness
$\bar{u}_i^j$ = in-plane displacement field due to the slipping and separation between sublaminates.
z_j = the z-coordinate of the delaminated interface.

$m =$ nodal position in the model
$M =$ total number of nodal points
$N =$ total number of vibration modes
$K =$ mode of vibration
$R =$ strain direction
$\varepsilon_m =$ mechanical strain for position "m"
$(\varepsilon_m)_{\mathrm{del}} =$ mechanical strain for a delaminated element
$\delta_m =$ damage index

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