Damage Assessment of Composite Plate Structures with Uncertainty

Chandrashekhar M, Ranjan Ganguli

DAMAGE ASSESSMENT OF COMPOSITE PLATE STRUCTURES WITH UNCERTAINTY

Chandrashekhar M.[*], Ranjan Ganguli[**]

[*] *Space Applications Centre, ISRO, Ahmedabad, 380015, India*
[**] *Department of Aerospace Engineering, Indian Institute of Science, Bangalore, 560012, India*

shekhar@sac.isro.gov.in

ABSTRACT

Uncertainties associated with a structural model and measured vibration data may lead to unreliable damage detection. Two similar structures made from composite materials can display very different dynamic behavior due to large uncertainties associated with composite material properties. In this paper, we show that material uncertainties in composite structures cause considerable problem in damage assessment which can be alleviated by using a fuzzy logic-based approach for damage detection. A recently proposed robust Fuzzy Logic System (FLS) with sliding window defuzzifier is used for delamination damage detection in composite plate type structures. The FLS is designed using variations in modal frequencies due to randomness in material properties. Probabilistic analysis is performed using Monte Carlo Simulation (MCS) on a composite plate finite element model. A recently developed Reddy type C^0 shear deformable locking free refined composite plate element is employed in the numerical simulations to alleviate modeling uncertainty. It is demonstrated that the FLS shows excellent robustness at very high levels of randomness in input data.

KEYWORDS : *damage detection, composite delamination, material uncertainty, Fuzzy Logic.*

INTRODUCTION

For any model based damage detection problem, characterization of changes in structural responses due to any structural damage is required to be known a priori. Use of an accurate mathematical model increases the chances of correct diagnosis in damage detection. Mathematical characterization of a damage in any composite structure is very difficult due to several damage modes and no unified mathematical theory is available which can combine all possible modes of damages in composite materials. Also, huge variation in structural response can be observed when using different theories for composite structures when compared with metallic structures. Further complications to the damage detection problem for composite structures is caused by large uncertainties associated with material properties of composite materials [1]. In this paper, the algorithmic development of the fuzzy logic system proposed by the authors in [2] is used for delamination detection in laminated composite plates having randomness in its material properties. The FLS is designed using variations in modal frequencies due to randomness in material properties. The probabilistic analysis is carried out using Monte Carlo Simulations.

1 MODELING

1.1 Modeling of composite plate

Chandrashekhar and Ganguli [3] recently proposed a refined shear deformable composite plate finite element model. It was demonstrated by them that their element performed better than the selected composite plate finite element models. In some situations, it was observed that the variation in first few frequency values can be of the order of more than 2 percent. The reason for using more refined theory is that a set of structural response parameters (e.g. frequencies or mode shapes) are required in a damage detection problem. Hence, the mathematical model used in structural characterization should be accurate enough even for higher modes which are used in the damage detection. The finite element discretization of a composite plate continuum leads to the following equation of motion for free vibration [3]

$$[M]\left\{\ddot{\Delta}\right\} + [K]\left\{\Delta\right\} = \{0\} \tag{1}$$

where [*M*] and [*K*] are mass and stiffness matrices respectively.

For given real symmetric matrices [*K*] and [*M*] in $R^{n\times n}$ and for some λ in *R* and ϕ in R^n,
Eq. (1) can be converted to a generalized eigenvalue problem

$$K\phi = \lambda M\phi \tag{2}$$

Solution of this eigenvalue problem gives *n* eigenvalues and corresponding *n* eigenvectors which represent the natural frequencies and natural mode shapes of the composite plate, respectively.

1.2 Damage modeling in the composite plate

Delamination damage is considered for the damage detection problem in a cantilever composite plate. Through delamination with different delamination lengths are considered. Three damage levels corresponding to different delamination lengths are considered. These delaminations are implanted at three different locations along the length of the cantilever composite plate. These locations are termed as “Inboard”, “Center” and “Outboard” with respect to the center position of the delaminated area in comparison to the plate length as shown in Fig. 1. Hence, three different damage levels at three different damage locations constitute nine possible damage conditions on the composite plate. Schematic of a dalamination damage at the “Center” location of the composite cantilever plate is shown in Fig. 1. The three different damage levels are simulated with through delaminations with lengths of 2.5 cm, 5 cm and 10 cm along the plate length. These damages are classified as “slight damage”, “moderate damage” and “severe damage”, respectively.

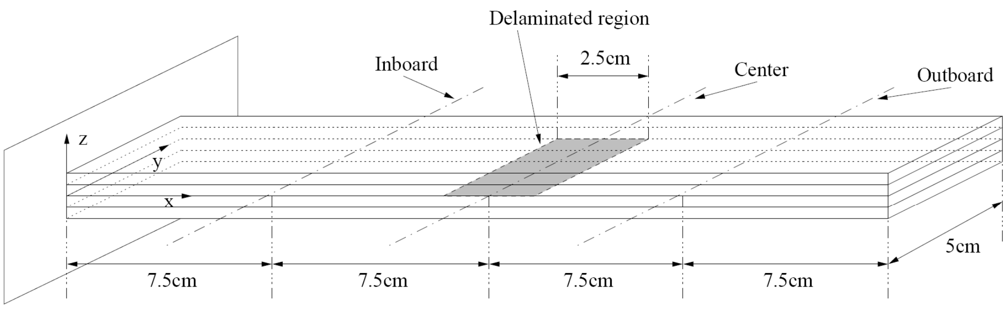


Figure 1: Schematic of a delaminated composite plate showing through delamination of 2.5 cm length representing “slight damage” at the “center location”

The modal parameter used in the delamination detection problem is the set of first six natural frequencies obtained from the structural simulations. The system indicator referred as “measurement delta (MD)” is the difference between the frequencies of undamaged and damaged plate, which is obtained using

$$\Delta\omega = \frac{\omega^{(u)} - \omega^{(d)}}{\omega^{(u)}}100 \tag{3}$$

Hence different combinations of the three damage levels with three different locations of the plate give different sets of $\Delta\omega$, which are used to create the knowledge base of fuzzy rules.

2 UNCERTAINTY EFFECTS ON DAMAGE PARAMETER

A cantilever plate made of $[0/90]_{4s}$ carbon cyanate composite material used by Chattopadhyay et al. [4] is considered for the delamination detection problem. The dimensions of the composite cantilever plate shown in Fig. 1 are length = 30 cm, width = 5 cm, and thickness = 0.218 cm. Numerical simulations are made by implanting delaminations in nine different combinations in the composite plate as explained earlier. The ply level location of delamination is the second interface from the mid-surface. The material properties are given in Table 1. First six natural frequencies obtained using the refined shear deformable composite plate element for the undamaged plate are 44.48, 134.41, 277.23, 465.11, 745.58 and 769.12 Hz, respectively.

Table 1: Material properties of the cantilever laminated composite plate

	Carbon cyanate
Young's Moduli (GPa):	
E_{11}	380.0
$E_{22} = E_{33}$	16.6
Poisson's ratio:	
$\nu_{12} = \nu_{13}$	0.31
ν_{23}	0.42
Shear Moduli (GPa):	
$G_{12} = G_{13}$	4.2
G_{23}	1.5
Density $\rho(kg/m^3)$:	1800

Sensitivity of $\Delta\omega$ with respect to different damage levels at various locations is shown in Fig. 2.

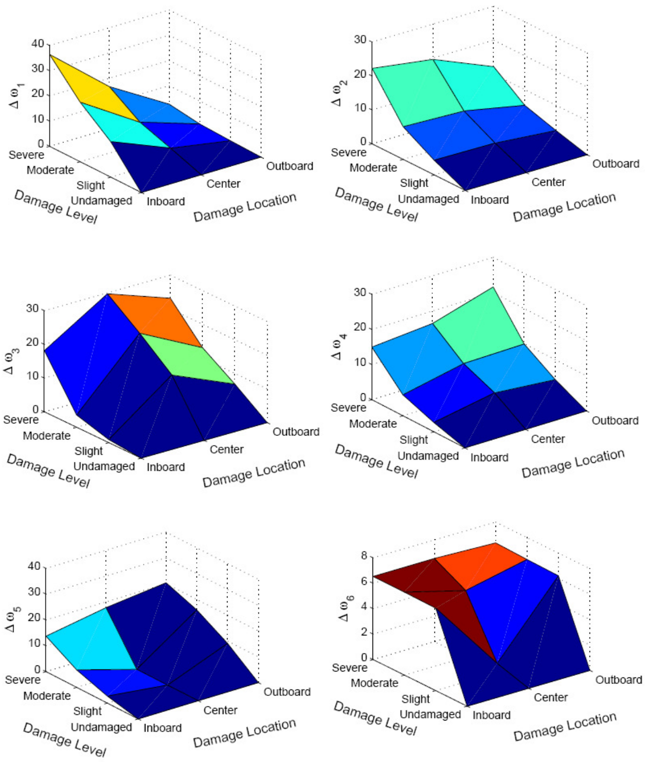
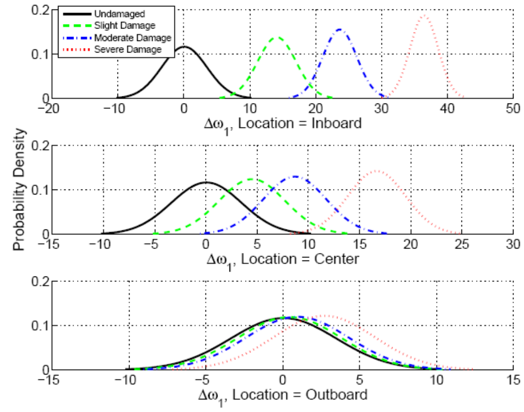


Figure 2 : Sensitivity plots for first six $\Delta\omega$ with respect to damage

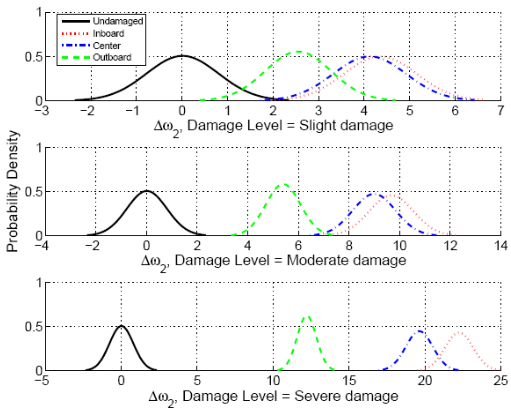
Monte Carlo Simulation (MCS) for 5000 input sampling points is used to obtain the variance of linear natural frequencies of the composite plate due to randomness in its constituent material properties. The variations in the macrolevel effective elastic moduli due to scatter of 5% COV in microlevel constituents (i.e. E_f, ν_f, E_m, ν_m, and V_f) are estimated by Onkar et al. [1]. The statistical values of first six measurement delta's estimated from MCS for 5000 input data points considering all of the individual material properties as independent random variables are given in Table 2. It can be seen that the standard deviations for these measurement deltas range from 0.97 to 3.47 percent.

Table 2: Statistical properties of the changes in first six natural frequencies for different damage conditions due to randomness in all of the composite material property constituents, simultaneously, shown as mean(standard deviation)

Damage Condition	$\Delta\omega_1$	$\Delta\omega_2$	$\Delta\omega_3$	$\Delta\omega_4$	$\Delta\omega_5$	$\Delta\omega_6$
Undamaged	0.0(3.47)	0.0(1.44)	0.0(3.47)	0.0(2.26)	0.0(2.39)	0.0(3.47)
Slight Damage at Inboard	14.12(2.93)	4.39(1.42)	0.96(3.38)	2.68(2.36)	2.81(3.29)	6.56(2.37)
Slight Damage at Center	4.52(3.26)	4.16(1.43)	14.85(2.91)	5.86(2.30)	0.05(2.52)	0.78(3.38)
Slight Damage at Outboard	0.46(3.40)	2.59(1.51)	6.89(3.18)	4.38(2.32)	9.13(3.10)	6.33(2.35)
Moderate Damage at Inboard	23.68(2.60)	9.71(1.25)	3.701(3.29)	6.01(2.28)	6.80(3.18)	6.63(2.35)
Moderate Damage at Center	8.69(3.12)	9.03(1.29)	22.67(2.64)	9.61(2.22)	0.30(2.72)	5.10(2.99)
Moderate Damage at Outboard	0.97(3.38)	5.44(1.44)	13.12(2.97)	9.93(2.18)	15.97(2.87)	6.38(2.35)
Severe Damage at Inboard	36.48(2.17)	22.28(1.31)	18.20(2.79)	15.00(2.06)	13.78(2.93)	6.64(2.35)
Severe Damage at Center	16.69(2.84)	19.66(1.26)	29.80(2.39)	16.48(2.03)	17.79(2.80)	6.65(2.35)
Severe Damage at Outboard	2.71(3.32)	12.25(0.97)	23.19(2.62)	21.62(1.90)	20.39(2.71)	6.452.35)



(a) Overlaps in $\Delta\omega_1$ for different damage levels at different locations



(b) Overlaps in $\Delta\omega_2$ for different locations at different damage levels

Figure 3: Variation and overlaps in the damage indicator due to material randomness

Variation in the damage indicator corresponding to first two natural frequencies due to randomness in material property is shown in Fig. 3. It can be seen that there are large overlaps in the MD $\Delta\omega$'s (the damage indicator) for various faults due to uncertainty in the physical parameter. The variability in the measurement delta (MD) due to material randomness is very high compared to the changes in the structural response due to damage itself. Making any direct damage assessment with this level of uncertain response data is very difficult.

The aleatory or random uncertainty in the composite material property causes a very high level of ambiguity in damage classification. Improper mathematical model used in the numerical simulation can also lead to uncertainty in structural response called epistemic uncertainty. It can be seen from Fig. 3(b) that in addition to the random uncertainty in the material properties if modeling or epistemic uncertainty of 2 percent is further added on the $\Delta\omega$'s (i.e. for $\Delta\omega_2$) the damage parameter will become almost completely overlapped for different damage conditions. Making accurate damage assessment with this highly uncertain data shall then become almost impossible. It was shown by the authors in [3] with numerical examples that their proposed composite plate finite element model is more accurate than an earlier proposed refined composite plate element by Nayak et al. [5]. It was also shown that the difference in the natural frequencies obtained from these two different refined composite plate models can be even more than 2 percent for some shear flexible sandwich structures in first five frequency modes only.

3 FUZZY LOGIC SYSTEM FOR DAMAGE DETECTION:

A recently proposed robust Fuzzy Logic System (FLS) with sliding window defuzzifier is used for delamination damage detection in the composite plate structure.

Here, we use changes in first six natural frequencies ($\Delta\omega$) obtained from the numerical simulations as input to the FLS. Each of the input measurement deltas are fuzzified using Gaussian membership functions. The selection of the standard deviation for the fuzzy set is a key feature, as it affects the performance of the FLS. The fuzzy sets should have enough width to capture the variations in the measurement delta's. Therefore, the maximum of the standard deviations (3.47 percent) for variation in the measurement delta's obtained from MCS (Table 2) is selected so as to allow a high level of uncertainty alleviation in damage detection. The details about the formulation of the FLS to handle uncertainty is given in [2].

The fuzzy logic system is tested using measurement deltas obtained from the FE model considering randomness in all of the composite material properties simultaneously representing maximum physical uncertainty and further contaminated with measurement noise. Hence, for each of the nine delamination damage conditions, five thousand noisy data points are used for testing the FLS and the percentage success rate from the fuzzy system in classifying a fault is calculated. Table 3 shows the success rate for the nine different damage conditions for different levels of measurement noise (α = 0.1, 0.15 and 0.2). Noisy input to the FLS is generated using

$$\Delta\omega_{noisy} = \Delta\omega_{random}(1 + u\alpha) \tag{4}$$

where, $\Delta\omega_{random}$ is the calculated measurement delta or the randomized measurement delta obtained from MCS, u is a random number in the interval [-1, 1], and α is a noise level parameter.

Table 3: Success rate of the FLS with sliding window defuzzifier at different noise levels (α)

Damage Condition	**α = 0.10**	**α = 0.15**	**α = 0.20**
Undamaged	99	98	96
Slight Damage at Inboard	94	91	86
Slight Damage at Center	84	83	77
Slight Damage at Outboard	91	87	82
Moderate Damage at Inboard	98	97	94
Moderate Damage at Center	89	87	84
Moderate Damage at Outboard	96	95	93
Severe Damage at Inboard	99	98	96
Severe Damage at Center	96	94	91
Severe Damage at Outboard	98	97	95
Avg. SR.	94.4	92.7	89.4

It can be seen that even for the case when the changes in damage parameter due to material randomness and measurement uncertainty are comparable to the changes in MDs due to damage itself, the FLS demonstrates robustness in classifying delamination damage in the composite plate structure.

CONCLUSION

The effects of changes in the damage evaluation parameter (frequency) due to material randomness are explored for a composite plate structure. Probabilistic analysis is performed using Monte Carlo Simulation (MCS) on a refined composite plate finite element model to calculate statistical properties of the variation in modal parameters of the cantilever composite plate due to structural damage and material uncertainty. The effects of epistemic uncertainty in damage detection is described which could come from inaccurate mathematical modeling. The FLS shows excellent robustness with highly randomized and noisy data using the modal based measurement delta. The applicability of the FLS is demonstrated for a realistic problem of delamination detection in composite plate type structures having very high randomness in its material properties.

REFERENCES

[1] A.K. Onkar, C.S. Upadhyay, D. Yadav, Stochastic Finite Element Buckling Analysis of Laminated Plates with Circular Cutout under Uniaxial Compression. *Journal of Applied Mechanics,* 74(4):798–809, 2007.

[2] M. Chandrashekhar and R. Ganguli, Uncertainty Handling in Structural Damage Detection using Fuzzy Logic and Probabilistic Simulation. *Mechanical Systems and Signal Processing,* 23(2):384–404, 2009.

[3] M. Chandrashekhar and R. Ganguli, Nonlinear Vibration Analysis of Composite Laminated and Sandwich Plates with Random Material Properties. *International Journal of Mechanical Sciences,* 52(7):874–891, 2010.

[4] A. Chattopadhyay, H.S. Kim, A. Ghoshal, Nonlinear Vibration Analysis of Smart Composite Structures with Discrete Delamination using a Refined Layerwise Theory. Journal of Sound and Vibration, 273:387–407, 2004.

[5] A.K. Nayak, S.S.J. Moy, Shenoi, Free Vibration Analysis of Composite Sandwich Plates Based on Reddy's Higher-order Theory. Composites: Part B, 33(7):505–519, 2002.