Free Vibration Analysis of Damaged Composite Laminates Using FEA and EMA

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NSC Project No.：NSC-92-2212-E-020-010

Abstract

This paper presents the free vibration analysis of damaged composite laminates at completely free boundary condition using finite element analysis (FEA) and experimental modal analysis (EMA). Carbon/epoxy composite AS4/PEEK was used to fabricate rectangular symmetrical laminates $[0]_{16}$ and $[(0/90)_4]_S$. A surface crack was created at the location near the center of the laminate plate. Linear solid element was adopted to model the laminate plates using a FEA commercial code. Mass effect of accelerometer was considered into the finite element model. The natural frequencies and the associated mode shapes obtained from FEA were verified by EMA. A good agreement between these two results was obtained.

Keywords: FEA, Free vibration, Damaged composite laminates, EMA

1. Introduction

The vibration methods were increasingly adopted in the detection of damage in composite materials due to their flexibility of measurement and relatively low cost. Cawley and Adams [1] indicated that damage in composite laminates could be detected by the change of natural frequencies of the laminate. Subsequently, the free vibration problems of damaged and undamaged composite laminates have been investigated by significant number of papers. Most of the studies approached the problems using both analytical (closed-form, Galerkin, Rayleigh-Ritz) method and numerical methods. Theories of beams, plates, or shells were usually used to model composite laminates especially in simulating the damage problems. In these researches, the developments of beam models were investigated by Majumdar and Suryanarayan [2], Tracy and Pardoen [3], and Shen and Grady [4] based on either Euler beam or Timoshenko beam theories. Plate models were discussed by Barbero and Reddy [5], Moorthy and Reddy [6], and Ju et al. [7] based on layerwise theory. All the above researchers focused their study on the damage of delamination in composite laminates. In their models, composite laminate was subdivided into damaged and undamaged span-wise regions, which can be modeled as either beam or plate. Nevertheless, few researches were done for investigating other types of damage such as thickness-wise crack.

Recently, the use of FEA commercial codes in studying composite materials has increased dramatically due to its flexibility of modeling. Hu et al. [8] adopted solid element model to simulate the composite symmetrical laminate plates. This FE model provided efficient and accurate calculation of the natural frequencies and the associated mode shapes for the laminate plates without cumbersome mathematical formulation.

The objective of this paper is to study the free vibration of damaged composite laminates by using FEA and EMA. Solid element was adopted to model the damaged laminate plates. Modal analysis was performed to obtain the natural frequencies and the associated mode shapes of the damaged plates. The FEA results were validated by the EMA results. The verified FE model provides help to analyze the problems of damage detections in composite laminates.

2. Finite element analysis

A finite element model was established to model a composite laminate plate with dimension 209×126×2.4 mm^3. ANSYS, a FEA commercial code, was used in this study. Eight-node linear solid element (SOLID46) was used in the modeling. The element provides a layered version allow up to 250 different material layers. To simulate a 31 mm-long, 0.2 mm-wide and 1 mm-deep surface crack, nodes at the location of surface crack were replaced by separated nodes. Figure 1 shows the finite element model of composite laminate plate.

Two symmetrical laminate plates, i.e., $[0]_{16}$ and $[(0/90)_4]_S$ were investigated in this study. A convergence study was performed to obtain a 40×30×8 mesh model, which is sufficient to solve the normal mode problem. The mechanical properties (E_1 = 140.3 GPa, $E_2 = E_3$ = 9.4 GPa, $G_{12} = G_{13}$ = 5.4 GPa, $\nu_{12} = \nu_{13}$ = 0.253) of composite AS4/PEEK were entered into ANSYS. These data were obtained from the quasi-static tensile tests of composite material. Hu et al. [8] found that the effects of out-of-plane shear modulus G_{23} and Poisson's ratio ν_{23} on the natural frequencies are not critical in thin plate. Thus, the values of G_{23} and ν_{23} were assumed to be the same as G_{12} and ν_{12} in this study. Material density was directly measured from laminate plates, i.e., ρ=1485kg/m^3 for laminate $[0]_{16}$ and ρ=1537kg/m^3 for laminate $[(0/90)_4]_S$.

A normal mode analysis with completely free boundary condition was performed to obtain the natural frequencies and the associated mode shapes up to 2 kHz. The first ten modes were extracted for analysis. Hu et al. [8] found that the mass of accelerometer significantly affects the natural frequencies of laminate plate. Thus, a mass element (MASS21) with 0.002 kg was assigned to fix at the laminate plate model.

3. Experimental modal analysis

Carbon/epoxy composite AS4/PEEK was used in this study. Symmetrical laminates, $[0]_{16}$ and $[(0/90)_4]_S$, were fabricated by stacking up the prepreg lamina and then cured at a hot-press machine. After curing, the panel was cut to a 209×126×2.4 mm^3 laminate using a diamond saw. A 31 mm long and 1 mm deep surface crack was created at the location near the center of the plate using a laser cutting machine.

Figures 2 and 3 show the test plate and the experimental setup. Laminate plate was marked to 13×13 parallel grid points, and vertically hung by two cotton strings to simulate a completely free boundary condition. Modal testing was conducted on the laminate plate. The plate was excited by an impact hammer with a force transducer throughout all grid points. The dynamic responses were measured by an accelerometer fixing at the corner. Siglab, Model 20-40, was used to record the frequency response functions (FRFs) between measured acceleration and impact force. ME'Scope, a software for the general purpose curve fitting, was used to extract modal parameters, i.e., natural frequencies, damping ratios and mode shapes, from the FRFs.

4. Results and Discussions

The first ten natural frequencies of the laminate plates obtained from FEA and EMA are listed in Tables 1 and 2. The superscripts u denotes the results of undamaged plate and the superscript d denotes the results of damaged plate. Tables 3 and 4 show the associated mode shapes contours of the damaged plates.

In laminate $[0]_{16}$, good correlations of natural frequencies and associated mode shapes between the FEA and EMA were obtained except for the first mode. Both results show that natural frequencies decrease when laminate plate is damaged. It is reasonable that surface crack induces certain losses of stiffness in some particular modes as shown in Table 3. For instance, the third mode depicts a significant bending in the direction perpendicular to surface crack. Consequently, the natural frequency obtained from EMA drops around 3.4%.

In laminate $[(0/90)_4]_S$, good correlations of natural frequencies between the FEA and EMA were obtained except for the 2^{nd}, 5^{th}, 6^{th}, and 8^{th} modes. The deviations in these modes are around 10%, which is a little bit high. However, the associated mode shapes reveal that deformation contours of the above modes obtained from FEA and EMA are very much alike. Good agreements are also obtained for other mode shapes as shown in Table 4. Again, both results indicated that natural frequencies decrease when laminate plate is damaged. The effect is critical especially in the modes associated with significant bending in the direction perpendicular to surface crack.

5. Conclusions

Free vibration analysis of damaged composite laminates using FEA and EMA is presented in this paper. Both results indicated that natural frequencies decrease when laminate plate is damaged. Especially, the decrease is significant when the associated mode is bending-wise in the direction perpendicular to surface crack. Good correlations between FEA and EMA results in natural frequencies and the associated mode shapes were obtained. The results validate that solid element successfully simulates surface crack damage in composite laminate plates. This reliable model can be applied to further analysis of damage detection in composite laminates.

Acknowledgment

The authors would like to acknowledge the support of Taiwan National Science Council through grant No. NSC-92-2212-E-020-010.

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應用 FEA 與 EMA 在複合材料對稱疊層板之自由振動分析

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摘要

本論文採用有限元素分析(FEA)與模態實驗分析

(EMA)進行複合材料破壞疊層板之自由振動分析。ANSYS 為本文所採用之有限元分析軟體，實體元素用來模擬複合材料疊層板及表面裂縫，分析模型亦考慮加速計本身之重量。有限元分析所獲得之自然頻率與相對應模態振形均與實驗模態分析之結果相當吻合，驗證了分析模型的準確度，以作為進一步複合材料疊層板之破壞檢測分析。

關鍵字：自由振動，複合材料對稱疊層板，有限元素分析，實驗模態分析

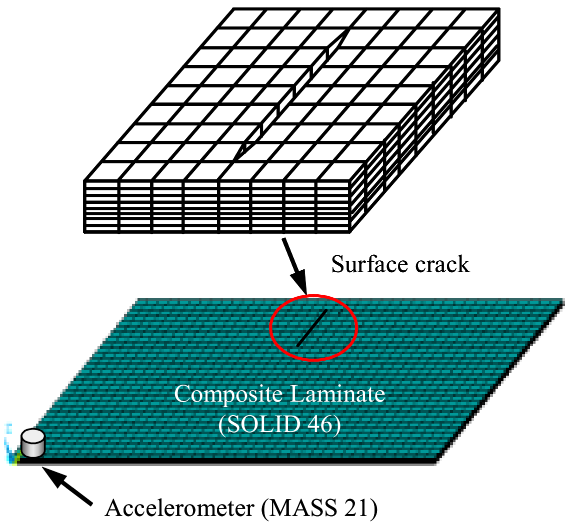


Fig.1 Finite element model for damaged laminate plate

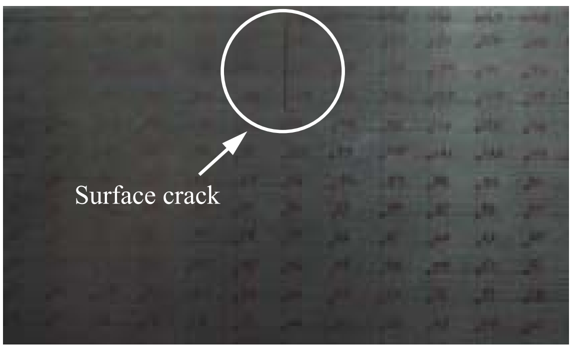


Fig.2 Test laminate plate

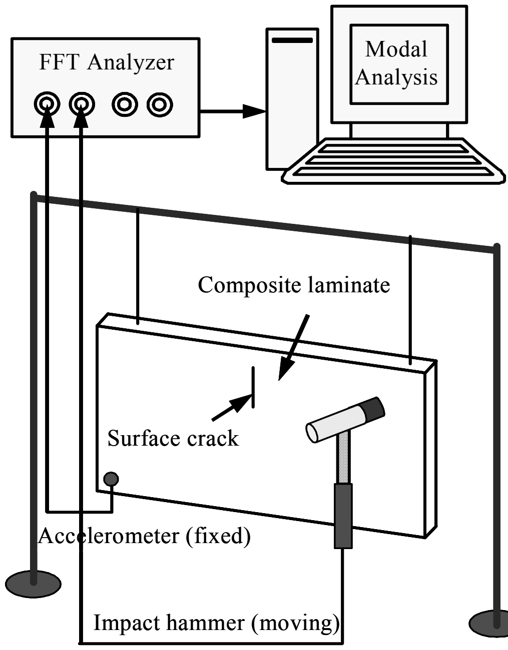


Fig.3 Experimental Set-up

Table 1 Natural frequencies of laminate plate $[0]_{16}$

	Natural Frequency (Hz)					
Mode shape	FEA[u]	FEA[d]	△ (%)	EMA[u]	EMA[d]	△ (%)
(2,2)	156	156	0.0	181	179	-1.1
(1,3)	342	342	0.0	349	349	0.0
(2,3)	435	430	-1.1	440	426	-3.2
(3,1)	502	494	-1.6	482	474	-1.7
(3,2)	578	565	-2.2	549	528	-3.8
(3,3)	832	827	-0.6	834	831	-0.4
(1,4)	979	978	-0.1	946	945	-0.1
(2,4)	1070	1070	0.0	1050	1050	0.0
(4,1)	1289	1288	-0.1	1190	1190	0.0
(4,2)	1408	1407	-0.1	1290	1290	0.0

Table 2 Natural frequencies of laminate plate $[(0/90)_4]_S$

	Natural Frequency (Hz)					
Mode shape	FEA[u]	FEA[d]	△ (%)	EMA[u]	EMA[d]	△ (%)
(2,2)	168	168	0.0	154	154	0.0
(3,1)	398	395	-0.8	361	360	-0.3

(3,2)	510	503	-1.4	486	483	-0.6
(1,3)	882	881	-0.1	846	843	-0.4
(2,3)	1018	1018	0.0	924	922	-0.2
(4,1)	1113	1113	0.0	1000	1000	0.0
(4,2)	1199	1199	0.0	1120	1120	0.0
(3,3)	1291	1290	-0.1	1170	1170	0.0
(4,3)	1730	1730	0.0	1680	1670	-0.6
(5,1)	2127	2127	0.0	1970	1970	0.0

Table 3 Mode shapes of damaged plate $[0]_{16}$

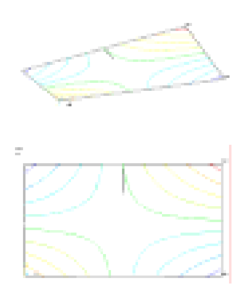
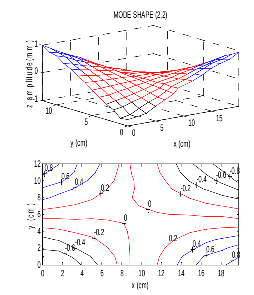
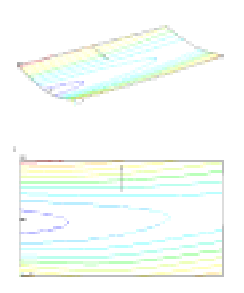
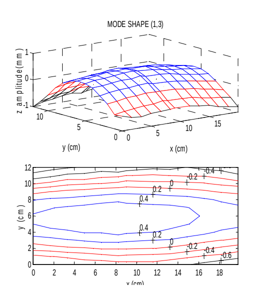
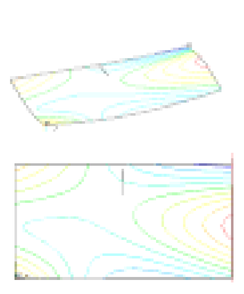
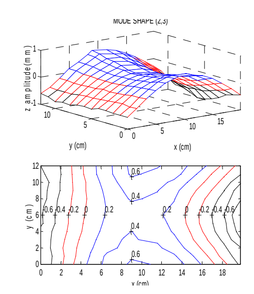
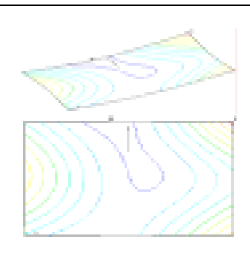
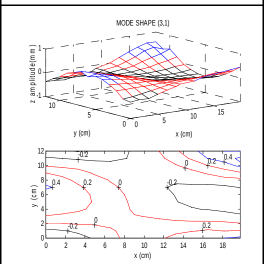
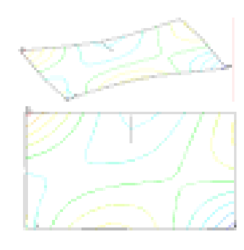
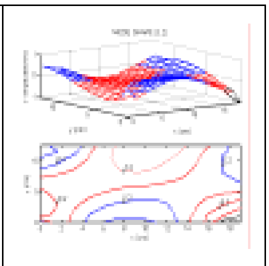
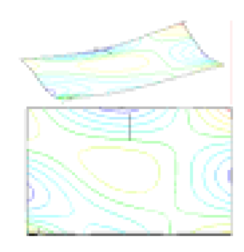
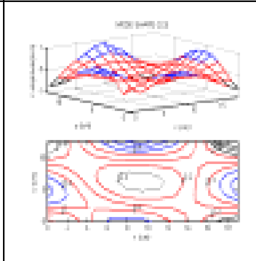
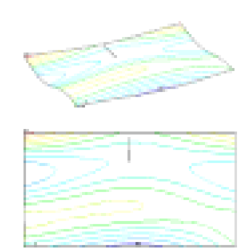
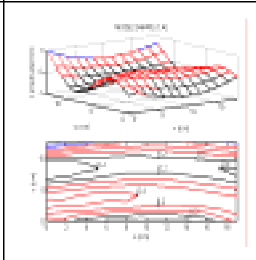
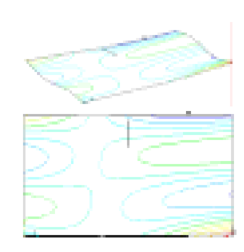
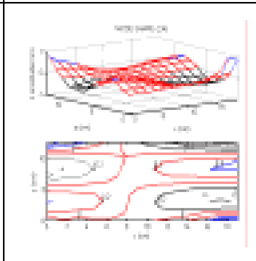
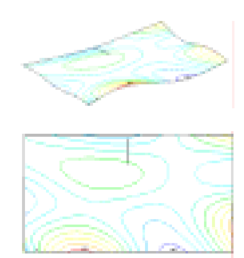
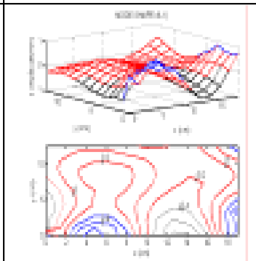
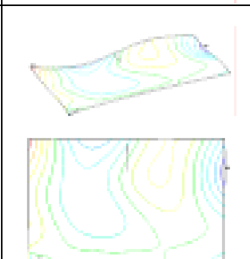
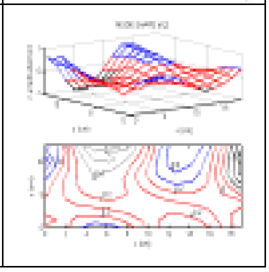
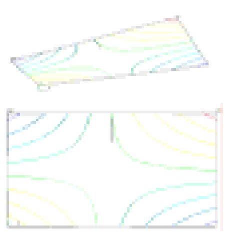
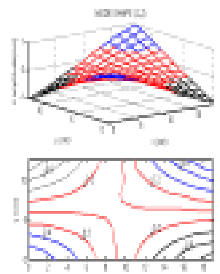
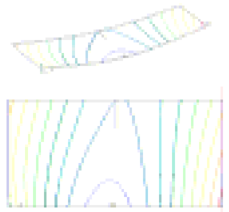
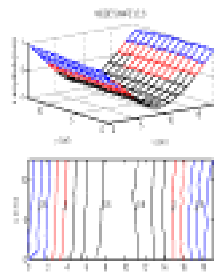
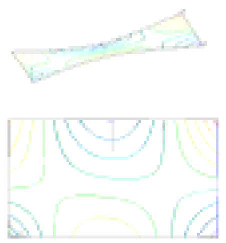
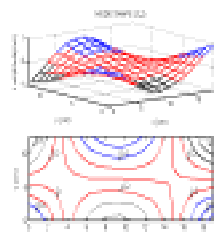
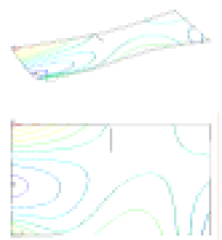
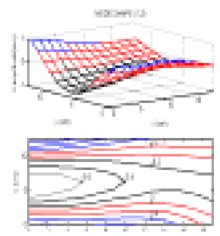
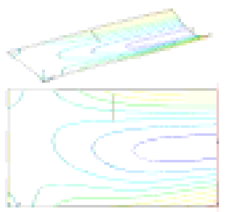
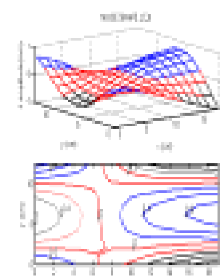
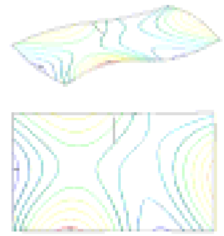
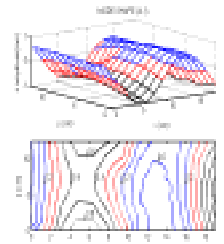
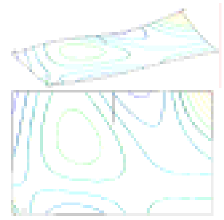
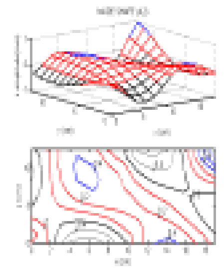
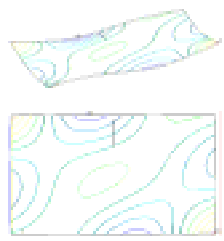
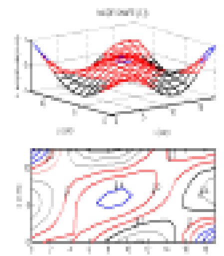
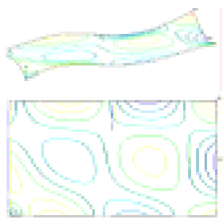
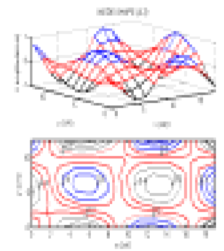
	FEA	EMA
(2,2)		
(1,3)		
(2,3)		
(3,1)		
(3,2)		
(3,3)		
(1,4)		
(2,4)		
(4,1)		
(4,2)		

Table 4 Mode shapes of damaged plate $[(0/90)_4]_S$

	FEA	EMA
(2,2)		
(3,1)		
(3,2)		
(1,3)		
(2,3)		
(4,1)		
(4,2)		
(3,3)		
(4,3)		
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