VIBRATION BASED ANALYSIS OF DELAMINATED/DAMAGED COMPOSITE BEAMS

BOJĀTU/ATSLĀŅOTU KOMPOZĪTMATERIĀLA SIJU VIBRĀCIJU ANALĪZE

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Introduction

Due to their advantages of stiffness and strength over homogeneous materials, composite materials are finding increasing use in a variety of engineering application such as aircraft, automobiles, sporting goods and electronics. On the other hand, the mechanical properties in composites may degrade severely in the presence of damage which may grow as a combination of such failure modes as matrix cracking, fiber pullout, fiber fracture, fiber-matrix debonding and delamination between plies. In this paper the effect of interplay delamination in graphite/epoxy composite beams as well as the effect of damage on dynamic parameters is studied.

Delamination, probably one of the most commonly occurring failure modes, appears as a debonding of adjoining plies in laminated composites. Delamination not only affects the strength of the structure but also cause a reduction in stiffness, thus affecting vibration characterizations. Recently, several studies have been conducted in the area of vibration behaviour of delaminated composites. The effect of delamination on vibration characteristics was studied by Grady and Meyn [1], Shen and Grady [2], Mujumdar and Suryanarayan [3] and Lee *et al.* [4]. Their experimental measurements showed that the natural frequencies of composite beams were significantly affected by the introduction of an interfacial delamination. Vibration behaviour of delaminated composite plates is studied by Campanelli and Engblom [5] and Ju *et al.* [6]. The object of proposed work is to investigate the effect of delamination on modal parameters using finite element method to model delamination with arbitrary size and location.

Damage as a combination of different failure modes in the form of loss of a local stiffness in a structure would alter its dynamic characteristics, i.e., the modal frequencies, mode shapes and modal damping values. In such cases, the change in vibration parameters can be used as indicators for damage detection. Research in vibration based damage detection has become a very active topic in recent years. Doebling *et al.* [7] and Zou *et al.* [8] gives excellent overviews of methods to detect, locate and characterize damage by examining changes in measured vibration parameters. In the present study the change in modal parameters, i.e., natural frequencies, mode shape curvatures and modal strain energy [9] is employed to evaluate the possibility to detect and locate damage.

Basic assumptions and Finite Element modelling

Model for delaminated beam

The geometry of the composite beam with an arbitrarily located trough-width delamination is shown in Fig.1. For the purpose of analysis, the beam has been subdivided into three spanwise regions – a delamination region and two integral regions. The undelaminated regions, indicated by beam 1 and 3, are modelled using layered eight noded shear deformable plate elements (ANSYS 8.1, Linear Layered Structural Shell element – SHELL99, [10]). Each node has six degrees of freedom: three displacements and three rotations.

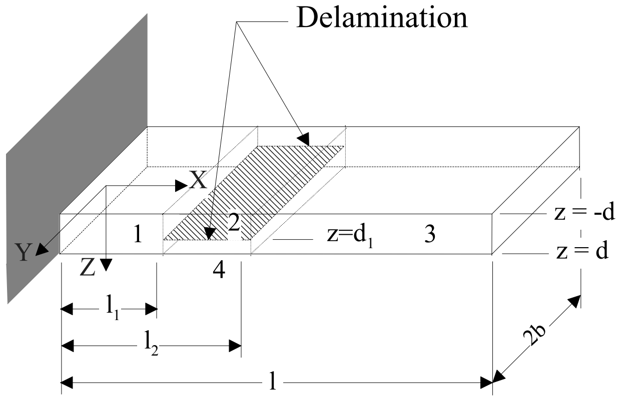

Fig. 1. Geometry of a composite laminated beam with delamination

The problem that must be addressed is how to represent the delaminated region. In Fig. 1. the delaminated region is divided into the upper plies (beam 2) and the lower plies (beam 4), and is made from two separate segments joined at their ends to the integral segments. At the interface between plies, two sets of nodes, on belonging to the upper ply, the other to the lower ply, are placed. These nodes occupy the same geometric position in space, but are allowed to vibrate independently.

Model for damaged beam

A simply supported finite element beam is used for this study. The finite element model for the beam consists of 10 equal length two dimensional beam elements (see Fig. 2.). Three degrees of freedom, translations along the X an Y axes and rotation along the Z axis are used at each node in the finite element analysis (ANSYS 8.1, 2D- Elastic Beam element – BEAM3, [10]). In actual structure damage will often affect the stiffness matrix but not the mass matrix of the system. In the theoretical development that follows, damage is assumed to cause a loss of stiffness in damaged elements of the system. For the intact beam a constant stiffness is assumed for all elements, while for the damaged beam reduction of stiffness for damaged elements is applied.

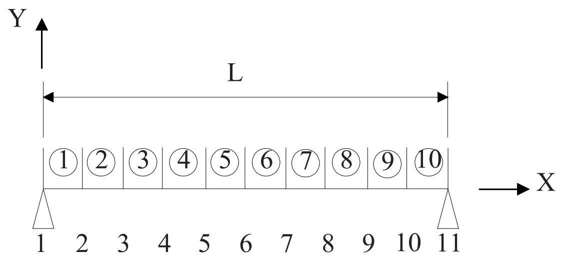

Fig. 2. Finite element model – simply supported beam

Computation of modal parameters

The eigenvalue problem for the harmonic vibrations can be represented by

$$\mathbf{Ku} = \omega^2 \mathbf{Mu} \tag{1}$$

where **K** is the global stiffness matrix, **M** is the global mass matrix and **u** is the displacement vector. The subspace iteration method is used in the finite element program to solve the eigenvalue problem.

Numerical examples

Example 1

The delamination is introduced as a debonding of adjoining plies in laminate composite beam. The geometry of the delaminated beam is show in Fig. 1. The delamination is assumed to be uniform trough the width of the beam and located arbitrarily, as defined by parameters l_1, l_2 and d_1.The numerical model is compared with experimental results [2] obtained from laminated beams consisting of eight ply $[0/90]_{2s}$ construction made from T300/934 graphite/epoxy prepreg. Laminated beam with dimensions 10 x 0.5 x 0.04 in. (254 x 12.7 x 1.016 mm) is clamped along half of its span to simulate 5 in. (127 mm) long and 0.5 in. (12.7 mm) wide cantilever beam with delamination of length of 1, 2, 3, and 4 in. (25.4, 50.8, 76.2, 101.6 mm) along one of the four ply interfaces shown in Fig.3. Nominal thickness of each ply is 0.005 in. (0.127 mm). Material properties used in the computations and also in the experiment are presented in *Table 1*.

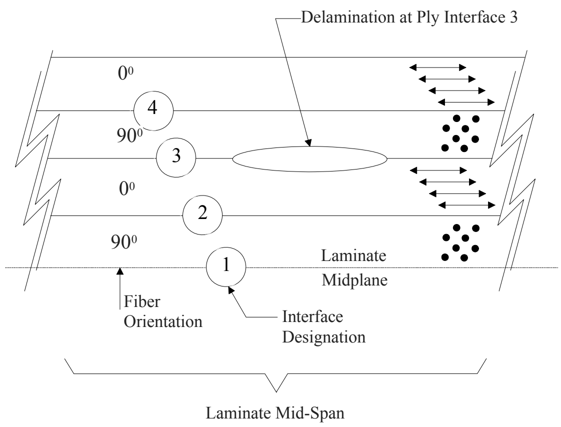

Fig. 3. Location of delamination in composite lamina

Table 1. Material properties of the laminated beam

E_{11}	19.5 x 10^6 psi	134.5 GPa
E_{22}	1.5 x 10^6 psi	10.3 GPa
G_{12}	0.725 x 10^6 psi	5.0 GPa
v_{12}	0.33	0.33
ρ	1.3821 x 10^{-4} lb-s^2/in.^{4}	1500 kg/m^3

The comparison of the first calculated and experimental natural frequencies [2] presented in *Tables 2* to *5* shows the effect of delamination size and interface location on the fundamental natural frequencies of the beam.

Table 2. First natural frequency for delamination along interface 1

Delamination length ($l_2 - l_1$), in. (mm)	Specimen 1, Hz [2]	Specimen 2, Hz [2]	Specimen 3, Hz [2]	Present FEM, Hz
0.0	79.875	79.875	79.750	82.117
1.0 (25.4)	78.376	79.126	77.001	81.064
2.0 (50.8)	74.375	75.000	76.751	74.665
3.0 (76.2)	68.250	66.250	66.375	63.723
4.0 (101.6)	57.623	57.502	57.501	53.837

Table 3. First natural frequency for delamination along interface 2

Delamination length ($l_2 - l_1$), in. (mm)	Specimen 1, Hz [2]	Specimen 2, Hz [2]	Specimen 3, Hz [2]	Present FEM, Hz
0.0	79.875	79.875	79.875	82.117
1.0 (25.4)	78.375	78.375	76.626	81.142
2.0 (50.8)	75.126	75.250	75.001	75.175
3.0 (76.2)	64.001	70.001	69.876	64.731
4.0 (101.6)	45.752	49.751	49.502	55.046

Table 4. First natural frequency for delamination along interface 3

Delamination length ($l_2 - l_1$), in. (mm)	Specimen 1, Hz [2]	Specimen 2, Hz [2]	Specimen 3, Hz [2]	Present FEM, Hz
0.0	79.875	79.875	79.750	82.117
1.0 (25.4)	79.625	80.125	80.625	81.853
2.0 (50.8)	79.500	81.875	77.875	80.150
3.0 (76.2)	75.625	77.125	78.125	76.384
4.0 (101.6)	73.376	73.627	70.376	71.537

Table 5. First natural frequency for delamination along interface 4

Delamination length ($l_2 - l_1$), in. (mm)	Specimen 1, Hz [2]	Specimen 2, Hz [2]	Specimen 3, Hz [2]	Present FEM, Hz
0.0	79.875	79.875	79.750	82.117
1.0 (25.4)	75.375	75.250	80.625	81.843
2.0 (50.8)	69.376	75.250	77.875	80.312
3.0 (76.2)	65.375	68.001	78.125	76.941
4.0 (101.6)	52.750	57.876	70.376	71.526

Example 2

The effect of damage in composite beam on natural frequencies, mode shapes and modal strain energy is studied introducing damage in the form of a loss of local stiffness in the beam. A simply supported finite element beam model is constructed using 10 beam elements as shown in Fig. 2. The graphite/epoxy composite beam with dimensions 1 x 0.2 x 0.05 m is represented assuming a constant Young's modulus for all elements. To simulate damage in the model, a reduction of the Young's modulus by 10% (90% of undamaged), 50% (50% of undamaged) and 90% (10% of undamaged) is applied to elements 5 and 6. Material properties of the graphite/epoxy composite beam used in the computations are presented in *Table 6*.

Table 6. Material properties of the graphite/epoxy composite beam

E_{11}	172.88 [GPa]
E_{22}	10.95 [GPa]
G_{12}	6.35 [GPa]
G_{23}	5.82 [GPa]
v_{12}	0.337
ρ	1598 kg/m^3

The effect of damage is represented as a ratio of change in modal parameters of composite beam. The ratio of change in natural frequencies is defined as

$$\Delta f = \frac{f_i - f_i^d}{f_i} * 100 \tag{2}$$

where f_i and f_i^d are natural frequencies of the undamaged and damaged state of laminated beam, respectively. The ratio of change for the first five natural frequencies and three damage states (90%, 50% and 10% of undamaged state) is shown in Fig. 4.

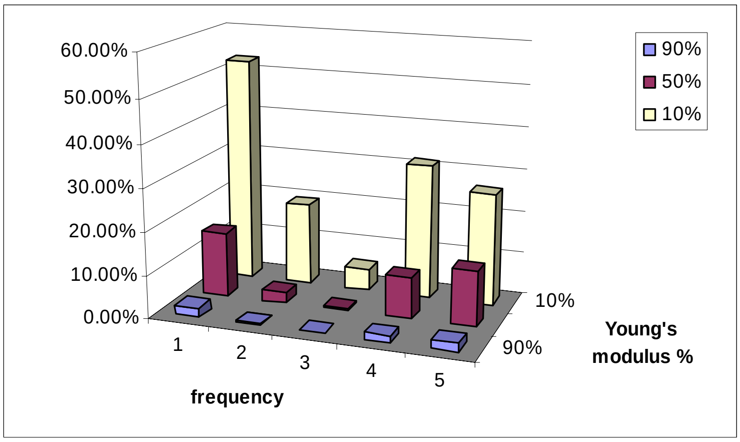

Fig. 4. Ratio of change in natural frequencies for composite laminated beam with delamination

From the results it can be seen that the ratio of change in natural frequencies indicates a reduction of the Young's modulus and a presence of damage in the structure, respectively. When the presence of damage in the structure is determined, the following interest is to detect its location in the structure. For the damage location a ratio of change in mode shape curvatures

(MSC) and modal strain energy (MSE) is employed. The ratio of change in mode shape curvatures (MSC) and modal strain energy (MSE) is stated as follows

$$\Delta MSE = \frac{MSE_{ij} - MSE_{ij}^{d}}{MSE_{ij}} * 100 \quad (3)$$

$$\Delta MSC = \frac{MSC_{ij} - MSC_{ij}^{d}}{MSC_{ij}} * 100 \quad (4)$$

where j and i denote the element number and mode number, respectively.
In the Fig. 5 to 7 the ratio of change in modal strain energy for the 1st, 2nd and 3rd natural frequencies is presented.

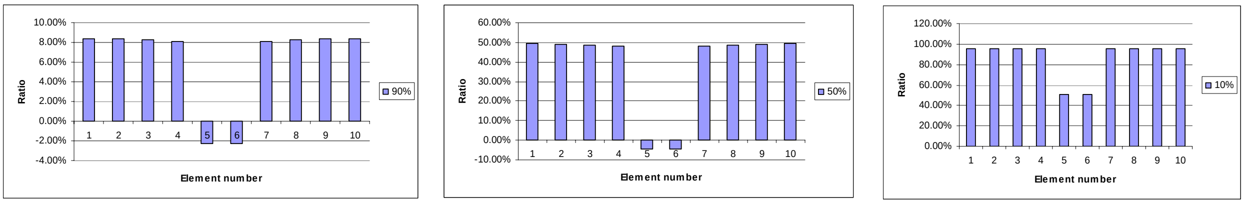

Fig. 5. The ratio of change in modal strain energy for the 1st natural frequency

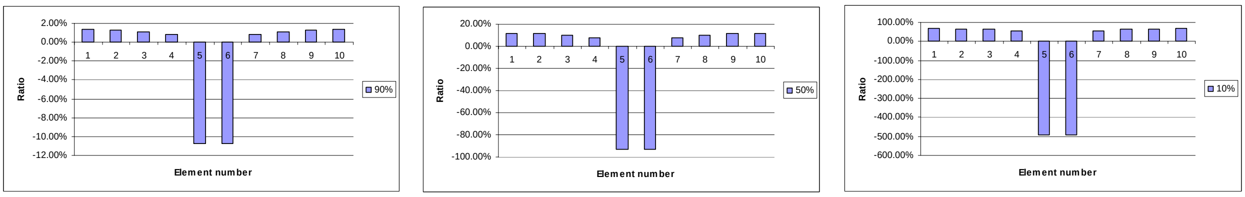

Fig. 6. The ratio of change in modal strain energy for the 2nd natural frequency

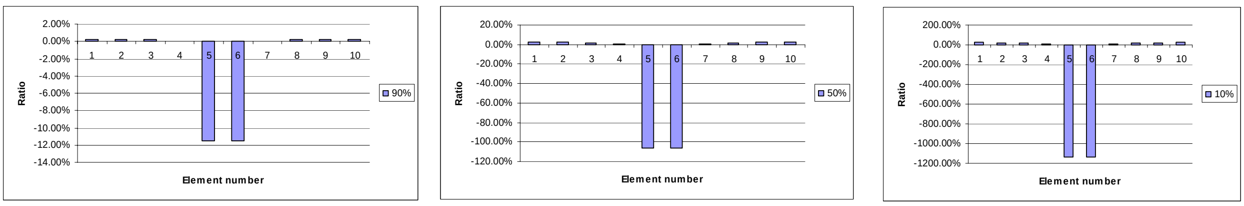

Fig. 7. The ratio of change in modal strain energy for the 3rd natural frequency

The results show clearly that the damage is present in elements 5 and 6, where it was originally introduced. In Fig. 8 to 10 the results of damage location by using the ratio of change in mode shapes curvatures for the 1st, 2nd and 4th natural frequencies are presented.
From the figures 8 to 10 it can be seen that also the ratio of change in mode shapes curvatures clearly indicates the presence of damage at node 6 which is a common node for damaged elements 5 and 6.

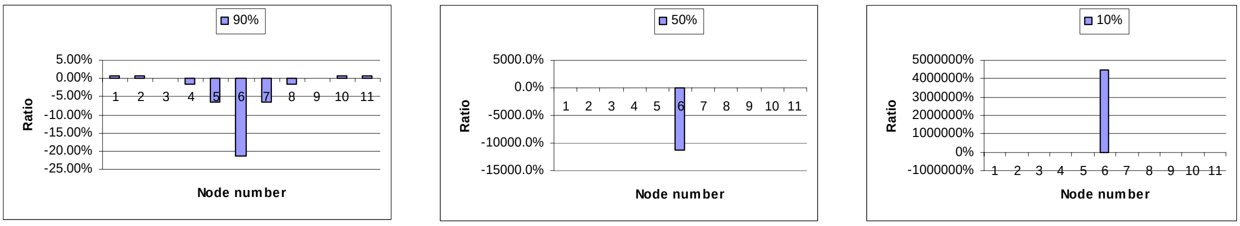

Fig. 8. The ratio of change in mode shapes curvatures for the 1st natural frequency.

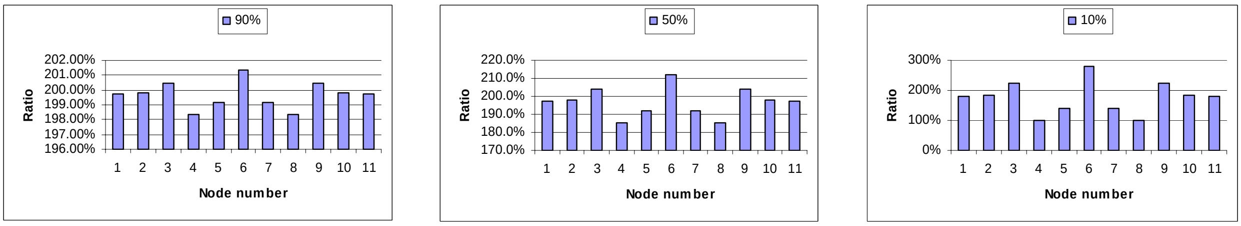

Fig. 9. The ratio of change in mode shapes curvatures for the 2nd natural frequency.

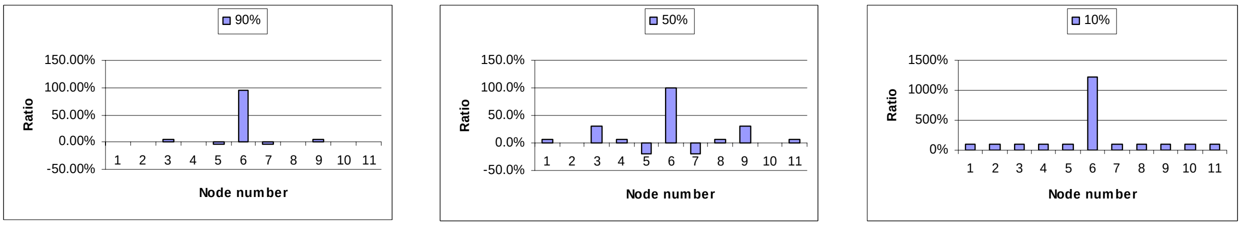

Fig. 10. The ratio of change in mode shapes curvatures for the 4th natural frequency.

Conclusions

A finite element study of the vibration characteristics of beams with delamination/damage has been presented in this paper. The numerical results presented point out that the effect of interplay delamination in graphite/epoxy composite beams on the natural frequencies depends not only on the size of delamination but also on its location. A damage localization method using the ratio of change in mode shape curvatures and modal strain energy clearly indicates the damage presence and its location in a structure. The results show that if the effect of the delamination/damage can be accurately predicted then changes in modal parameters could be used to determine the location and extent of delamination/damage in composite structure.

References

1. Grady J. E. and Meyn E. H. Vibration Testing of Impact-Damaged Composite Laminates // In: AIAA / ASME / ASCE / AHS / ASC/ 30th Structures, Structure Dynamics, and Materials Conference, Proceedings – Washington, 1989 – p. 2186 – 2193.
2. Shen H. and Grady J. E. Free Vibrations of Delaminated Beams // In: AIAA Journal, 30, 1992 – p.1361 – 1370.
3. Mujumdar P. M. and Suryanarayan S. Flexural Vibrations of Beams with Delaminations // In: Journal of Sound and Vibration, 125(3), 1988 – p. 441 – 461.

4. Lee B. T., Sun C. T. and Liu D. An Assessment of Damping Measurements in the Evalution of Integrity of Composite Beams // In: Journal of Reinforced Plastics and Composites, 6, 1987 – p. 114 – 125.
5. Campanelli R. W. and Engblom J. J. The Effect of Delaminations in Graphite/PEEK composite plates on modal dynamic characteristics // In: Composite Structures, 31, 1995 – p. 195 – 202.
6. Ju F., Lee H. P. and Lee K. H. Free Vibration of Composite Plates with Delaminations around Cutouts // In: Composite Structures, 31, 1995 – p. 177 – 183.
7. Doebling S. W., Farrar C. R. and Prime M. B. A Summary Review of Vibration-Based Damage Identification Methods // In: The Shock and Vibration Digest, 30, 1998 – p. 91 – 105.
8. Zou Y., Tong L. and Steven G. P. Vibration-Based Model-Dependent Damage (Delamination) Identification and Health Monitoring for Composite Structures – A Review // In: Journal of Sound and Vibration, 230(2), 2000 – p. 357 – 378.
9. Shi Z. Y. and Law S. S. Structural Damage Localization from Modal Strain Energy Change // In: Journal of Sound and Vibration, 218(5), 1998 – p. 825 – 844.
10. ANSYS. Version 8.1., 2004 ANSYS, Inc., Canonsburg, PA, USA

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Ručevskis S. Bojātu/atslāņotu kompozītmateriāla siju vibrāciju analīze
Rakstā tiek apskatītas konstrukciju raksturojošo dinamisko īpašību izmaiņas slāņainu kompozītmateriālu siju slāņu atslāņošanās kā arī bojājumu gadījumos. Izmantojot Galīgo Elementu metodi, tiek modelēts bojājums/atslāņošanās slāņainā kompozītmateriālu sijā un veikti aprēķini pašsvārstību frekvenču, pašsvārstību formu izliekumu un deformācijas enerģiju izmaiņu pētīšanai. Slāņainu kompozītmateriālu siju eksperimentālā un aprēķinu ceļā iegūtu pašsvārstību frekvenču salīdzinājums uzskatāmi parāda kā atslāņošanās laukuma lielums un tā atrašanās kompozītmateriālu sijā ietekmē fundamentālās pašsvārstību frekvences. Pašsvārstību formu izliekumu un deformācijas enerģiju izmaiņu koeficents ir izmantots, lai uzrādītu bojājuma esību un tā atrašanās vietu konstrukcijā.

Ruchevskis S. Vibration based analysis of delaminated/damaged composite beams
The effect of interplay delamination in graphite/epoxy composite beams as well as the effect of damage in the form of a loss of local stiffness in composite beams is evaluated. Finite element calculations of free vibrations of a composite beam with delamination/damage of arbitrary size and location are employed to study the effect of delamination/damage on natural frequencies, mode shapes and modal strain energy. The comparison of the calculated and experimentally obtained natural frequencies of the delaminated composite beam is performed to show the effect of delamination size and interface location on the fundamental natural frequencies of the beam. The ratio of change in mode shape curvatures and modal strain energy is employed to indicate the damage presence and its location in a structure.

Ручевскис С. Анализ колебаний слоистых композитных балок с дефектами в виде отслоения и разрушения слоёв.
В работе рассмотрены влияния на динамические свойства слоистой композитной балки дефектов в виде отслоения и разрушения слоёв. Эти эффекты модулировались с помощью метода конечных элементов. Получены изменения собственных частот и форм колебаний, а так же энергии деформаций от размеров и расположения областей отслоения и разрушения. Сравнение экспериментальных и численных данных собственных частот слоистой композитной балки показывает, что отслоения и место нахождения отслоения влияет на фундаментальные собственные частоты. Коэффициент изменения собственных частот и форм колебаний используется, чтобы показать наличие разрушения и его место нахождения в конструкции.