FE-Modeling of Fiber Reinforced Plastic Structures: Experimental Validation

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Summary:

This work deals with the experimental validation of the natural frequencies and mode shapes of simple fiber reinforced plastic structures, manufactured by resin transfer molding. The finite element (FE) models were built using Nastran shell elements with laminated composite (PCOMP) properties.

A systematic validation approach was chosen proceeding from a plate with with a unidirectional layup, to an open Z-profile with quasi-isotropic ply stacking, up to a two-piece double Z- profile joined by structural adhesive. Modern measurement techniques and NX Advanced Simulation pre- and post processing packages allowed the validation project to quickly complete with excellent results.

The following steps were followed to complete this study: The test specimens, in a free-free state, were excited by a shaker according to the results of a pre-test analysis. A 3D laser vibrometer attached to a robot arm was used to determine the frequency response of the structure. The natural frequencies and mode shapes were extracted and industry standard methods were used to quantify the degree of correlation between simulation and test: Modal Assurance Criteria (MAC), Coordinate MAC, and mode pairing. The sensitivities with respect to various model parameters were analyzed. Finally, model updating was performed within experimentally determined material property ranges.

Keywords:

Nastran, PCOMP, fiber reinforced plastics, validation, correlation, model updating

1 Introduction

The purpose of this work is to study the ability to predict the fundamental modes of simple composite structures typically used for automotive panel applications using the well established Nastran methods for shell modeling with PCOMP properties.

Composite structures have been analyzed successfully with Nastran since the 70s [1] and early 80s [2], including the simulation of fiber-reinforced composites [3]. Specific composites support has been available since the mid 80s through shell elements with PCOMP properties [4]. Sensitivity analyses and optimization of composite structures have also been conducted over the last three decades [5], including experimental validation [6]. Thus, the modeling approach used here can be considered as a standard approach to modeling thin-walled composite structures that has been used successfully for decades. However, for automotive applications, thoroughly verifying the predictability of this approach for the prospective application domain (such as the frequency range), verifying the correctness of the material properties, as well as gaining confidence in adequately using any new materials and manufacturing techniques is imperative when safety and comfort are important design considerations.

This paper is organized as follows: Section 2 describes some key concepts of the employed validation approach in terms of the choice of adequate test objectives, geometries, and methodologies – with the aim to arrive at a successful outcome of the project; some limitations of the approach are also mentioned. A brief description of the FE models is also presented for completeness. In Section 3, details are provided on how the modal tests were planned, conducted, and evaluated. In Section 4, the correlation results achieved are presented, comparing the original FE model to the physical test. Section 5 deals with sensitivity analyses, model updating, and related studies which were undertaken in order to gain more insight into the model behavior and major influences of the various model parameters on the predictability of the simulation results. Section 6 concludes with some lessons learned while undertaking this study.

Model building, analysis, correlation, sensitivity studies and model updating were performed using the NX software from Siemens PLM. Modal extraction was performed using Test for I-deas from Brüel & Kjær.

2 General Considerations and Simulation of the Composite Parts

2.1 Summary of Key Concepts and Limitations

2.1.1 Key Concepts

A few key concepts were applied over the course of the validation project to ensure its success. The simple models were analyzed prior to the more complex ones. Well-separated modes were ensured by simulation before manufacturing the test objects. Pre-test planning was carried out, including exciter selection. The modal tests were performed in a controlled environment (temperature, absence of external influences). As a reference, an isotropic steel plate was also modeled and tested.

2.1.2 Limitations

The study presented here does not include any quantification of uncertainties and their propagation through the analysis model, as in [6]. Furthermore, no repeated modal tests were performed on multiple test specimen with the same geometry to assess the degree of variability of the characteristics of the physical properties of the objects.

2.2 Description of the Modeling Approach

The FE models of the plates were built with uni-directional and quasi-isotropic ply stacking. Initially, the dimensions of the plates were not fixed, but instead, the geometry was varied in order to achieve well-spaced normal modes. This greatly simplified the downstream task of extracting mode shapes from the modal test results. To this end, the models were meshed from the CAD geometry with pre-processing software allowing for associative changes between the geometry changes and FE model discretization. Modern simulation environments allow the parametrization of geometries so they can be quickly modified and the mesh updated automatically by the pre-processor with the original meshing parameters, such as mesh width, element type, etc. The composite structures were defined by orthotropic material properties and ply stacking sequence (see Table 1) within the NX environment, the software translated these to Nastran MAT8 and PCOMP cards. The plate test structures and Z profiles were then fabricated in the same way.

Table 1: Ply stacking

Test specimen	*Ply angles of ply stack*	*Thickness per ply*
Unidirectional plate	$[0_{10}]$	0.2 mm
Quasi-isotropic plate Open Z profile Closed double-Z profile	[0/90/45/-45/0/90/-45/45/90/0]	0.2 mm

For the Z-profiles, the same quasi-isotropic ply stacking as for the quasi-isotropic plate was used. As with the plates, we ensured a geometry that exhibited well-separated modes in the frequency range of interest. For illustration, the final geometries – both test (left) and analysis (right), respectively – are shown in Fig. 1.

The closed double-Z-profile consists of two open Z-profiles that were joined by a structural adhesive. The adhesive was modeled as solid elements with a thickness of 0.2 mm referencing an isotropic material card.

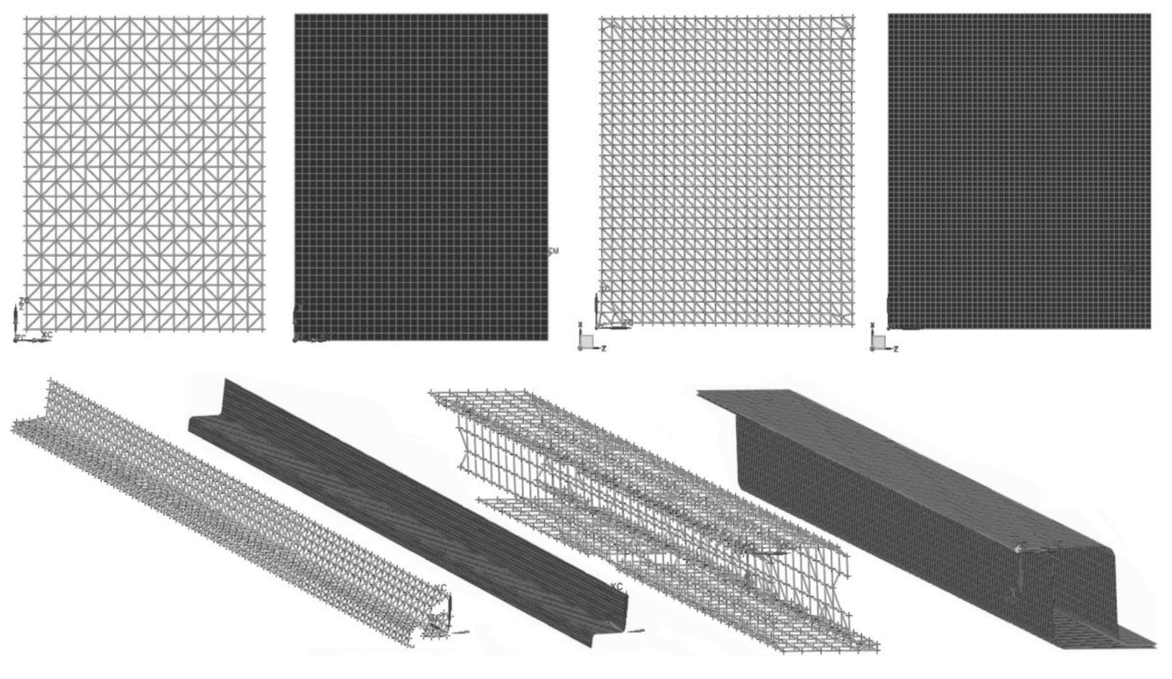


Fig. 1: Test and FE model geometries: Uni-directional, quasi-isotropic, Open Z, Closed Z

3 Test Preparation, Testing, and Application of Experimental Modal Analysis

3.1 Pre-Test Planning

Starting from a Nastran SEMODES 103 (normal modes) solution, suitable excitation locations were selected using Normal Mode Indicator Functions (NMIFs) by an algorithm described in [7]. The NMIFs represent the linearly accumulated (and normalized) synthesized frequency response functions (FRFs) for all prospective measurement points. Exciters are placed at locations where the NMIF function indicates good excitation of all modes.

In a similar fashion, test article suspension locations were selected at positions where the NMIF indicated low excitation. No automatic sensor selection was performed since the 3D laser non-contact measurement technique allows measurement of the response at hundreds of points, evenly distributed across the object geometry. The gaps that can be observed in the Z-profile test article meshes (see Fig. 1) are areas where the line of sight to the laser was obstructed. Another difference from the test article mesh to the FE mesh is that the dimensions were slightly modified since the vibrometer measurements cannot extend all the way to the edges of the test article.

3.2 Modal Tests

The modal tests were carried out by Polytec in Waldbronn, Germany. For all modal tests, a 3D laser-doppler vibrometer scanner was used. A shaker was used to excite the structures. It was connected to the structure via a 5 mm thick, 10 cm long plastic stinger that was in turn connected to an impedance head to measure the excitation force. The impedance head was secured to the plate's surface using ceramic glue. In the case of the open Z-profile, a water-based retro-reflective paint was used to increase backscattering in order to compensate for to the rather large measurement distance. In the case of the closed double-Z-profile, the scanner was mounted on a robot arm in order to move the position of the scanner automatically during data acquisition such that both sides of the profile were covered. Some images of the test setup are shown in Fig. 2, the data acquisition parameters are summarized in Table 2.

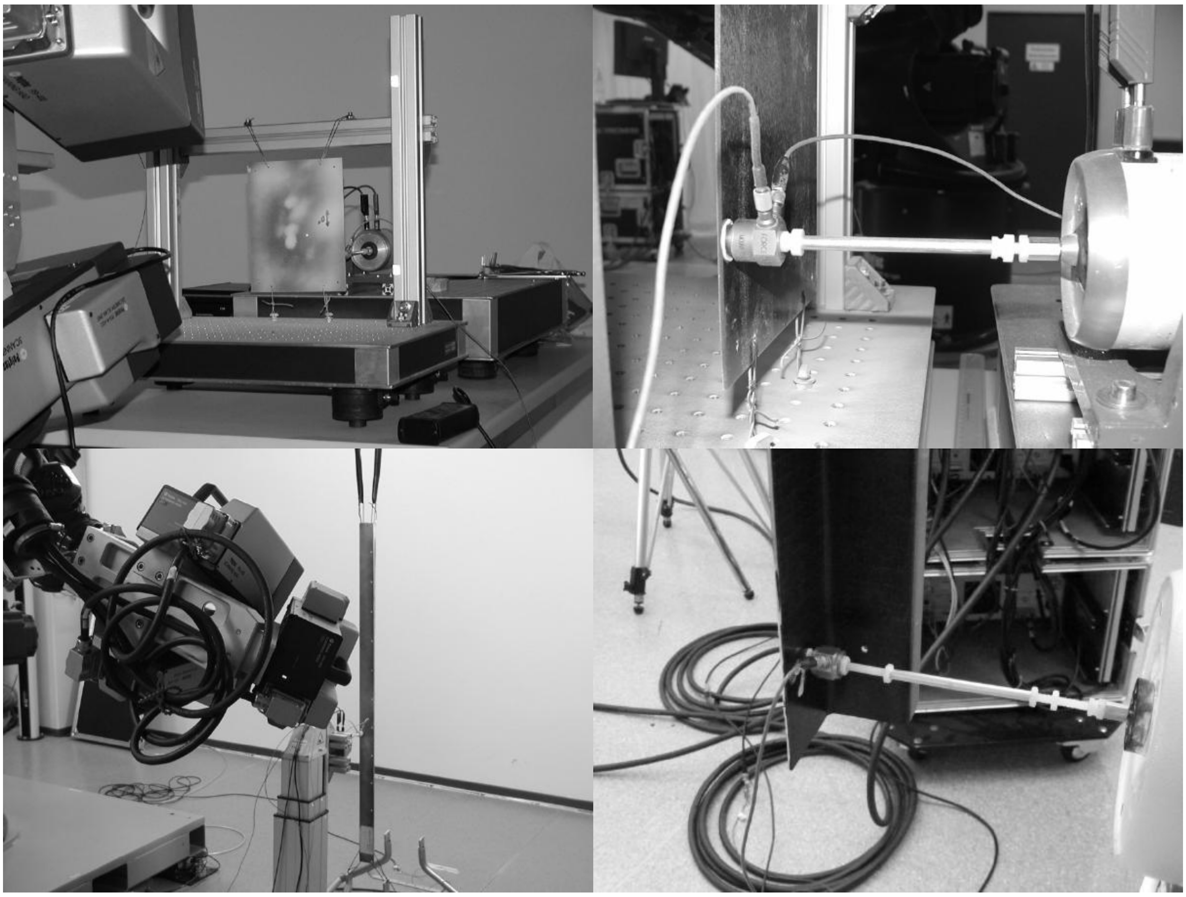


Fig. 2: Setup uni-directional plate (top), closed Z (bottom left), open Z (bottom right)

The main results that were used for further analysis consisted of mobility frequency response functions [8] (velocity over excitation force) at the measurement grid in x, y, and z directions. For all tests, a single point of excitation was sufficient to excite all modes of interest. The results showed very little noise.

Table 2: Test setup characteristics

Characteristic	*Uni-directional plate* *Quasi-isotropic plate* *Closed Z profile*	*Open Z profile*
Frequency bandwidth	Up to 1000 Hz	Up to 1100 Hz
Frequency resolution	0.5 Hz	0.5 Hz
Grid size (points)	374 / 750 / 1150	700
Type of excitation	Pseudo-random	White noise
Window	Rectangle	Hanning
Number of complex averages	20	32
Weight of stinger	5 g	5 g
Weight of impedance head	21 g	24 g

3.3 Modal Parameter Extraction

From the mobility FRF, only the imaginary part was used by the curve fitting algorithm. A standard single input, multiple output, frequency domain, polyreference technique [8,9] was used to extract the natural frequencies, mode shapes, and damping. For the plates, only the FRFs from the measurements normal to the plate were used, and similarly, for the Z-profiles, the FRFs in the direction of the longitudinal axis were ignored. The modal parameter extraction results are summarized in Table 3. The damped natural frequencies were within 1 Hz of the undamped natural frequencies for all specimens.

Table 3: Modal parameter extraction results

Object	*Extraction range*	*Number of extracted modes*	*Modes 1-6 undamped natural frequencies [Hz]*	*Damping range [%]*
Reference steel plate	100-1000 Hz	9	174, 206, 358, 404, 481, 599	0.1 to 1.3
Uni-directional plate	100-950 Hz	14	106, 170, 249, 317, 366, 412	0.6 to 1.9
Quasi-isotropic plate	50-1000 Hz	19	66, 117, 172, 175, 211, 314	0.3 to 1.5
Open Z profile	10-1050 Hz	27	41, 93, 122, 195, 285, 286	0.2 to 2.4
Closed Z-profile	100-1000 Hz	6	177, 318, 474, 657, 840, 904	0.1 to 0.7

The accuracy of the extracted modes was checked by comparing the spatially averaged synthesized FRFs, obtained from the extracted modes, modal damping, and frequencies, to the spatially averaged measured FRF. Furthermore, to ensure that the data was not over-fitted, the uniqueness of the extracted modes was verified by computing the AutoMAC for the test mode shapes [8]. Fig. 3 shows these plots for the quasi-isotropic plate.

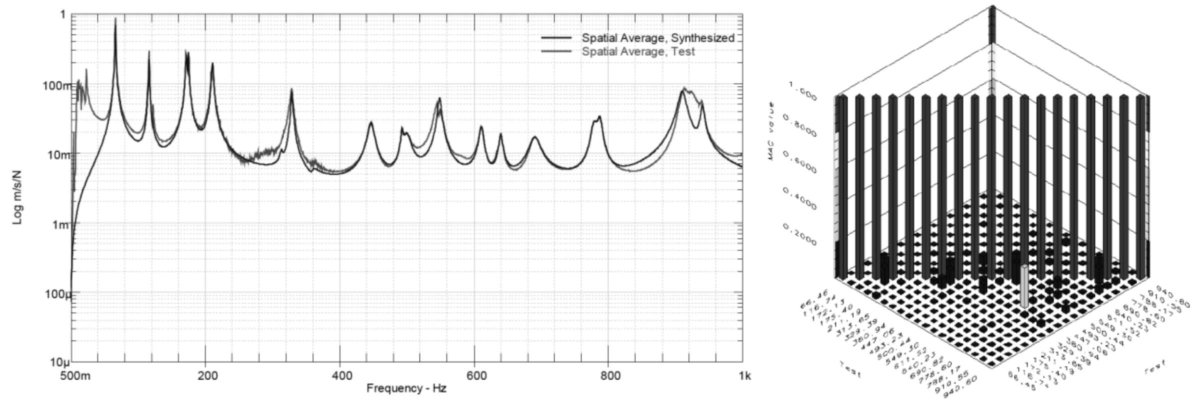


Fig. 3: Spatially averaged FRF and AutoMAC, quasi-isotropic plate

4 Baseline Correlation

4.1 Correlation Results

For each specimen, initial (baseline) correlations were conducted in order to assess the degree of agreement between the test and the FE model. More specifically, these were conducted for two material property configurations. A first set of laminate properties was estimated from comparable laminate properties found in the literature and the NX Laminate Composites material library. A second set of material data was derived from the uni-directional plate through a series of in-house tests. From the in-house tests, upper and lower bounds as well as the mean values were established.

MAC [8,10] values were computed in order to assess the degree of agreement between the test and the analysis mode shapes. Modes were paired based on a minimum pairing threshold. The results are shown in Tables 4 and 5.

Table 4: Baseline correlation results, properties from literature

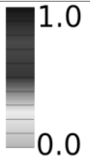
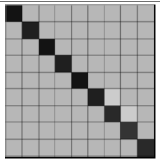
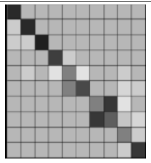
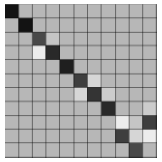
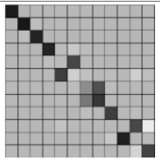
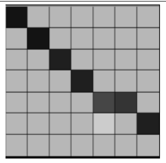
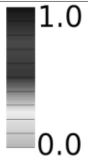
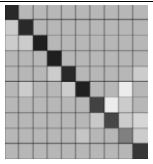
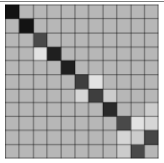
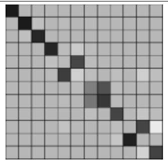
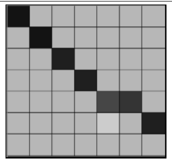
	Steel plate (ref.)	*Uni-dir. plate*	*Quasi-iso plate*	*Open Z profile*	*Closed Z profile*
MAC 					
Pairing threshold	0.7	0.6	0.7	0.5	0.7
# of modes paired	9	7	9	23	6
Average abs. freq. error	2.5%	14.4%	9.0%	15.5%	1.5%
Maximum abs. freq. error	6.4%	29.5%	21.3%	28.5%	3.6%
Average MAC	0.95	0.85	0.88	0.76	0.95
Minimum MAC	0.86	0.73	0.76	0.51	0.86

Table 5: Baseline correlation results, mean tested properties

	Uni-dir. plate	*Quasi-iso plate*	*Open Z profile*	*Closed Z profile*
MAC 				
Pairing threshold	0.6	0.7	0.5	0.7
# of modes paired	8	10	23	6
Average abs. freq. error	6.1%	11.5%	17.2%	2.3%
Maximum abs. freq. error	17.4%	25.8%	31.4%	4.3%
Average MAC	0.85	0.86	0.76	0.95
Minimum MAC	0.65	0.73	0.51	0.86

4.2 Interpretation of the Results

Overall, the agreement was found to be very good for the mode shapes, and the correlation results did not differ significantly between the two sets of material properties. This suggests that any differences were caused by well distributed, rather than local, effects (this claim was further supported by computing the Coordinate MAC). For the natural frequencies, a larger discrepancy between the two baseline correlation results was found only for the uni-directional plate where the properties determined in-house produced better correlation results (the average frequency error dropped from 14.4% to 6.1%). However, these improvements could not be carried over to the quasi-isotropic plate and the Z-profiles, possibly because other, ignored, effects were lumped into the measured orthotropic properties; these resulted in a better match for the specific plate used to derive the material values. For the closed double-Z-profile, all fundamental modes were very closely matched.

5 Sensitivity Studies and Model Calibration Results

5.1 Sensitivity Studies and Other Investigations

A number of sensitivity studies were conducted using the FE model to get better insight into where the differences between FE model and test could possibly originate, including: ply angles (of little influence); ply thickness (significant influence, in particular the outer plies of the plates, due to the increased offset from the neutral axis affecting the moment of inertia for out-of-plane bending); laminate material orientation (an incorrectly assigned material orientation can influence mode shapes significantly for quasi-isotropic laminates since isotropic behavior only holds for in-plane effects (see, e.g. [11]); laminate material properties (of small influence considering the given manufacturing tolerances – E1 and the in-plane shear modulus G12 appeared to have more significant influence than the other quantities). Convergence of the meshes was confirmed through successive refinement. The closed double-Z-profile showed virtually no sensitivity to the structural adhesive properties suggesting that the adhesive did not introduce any significant amount of damping to the system.

The test objects were also closely examined after the test. The plates were sliced in order to take photomicrographs. The photomicrographs showed that the ply by ply thickness varied significantly across the plates. Pockets of matrix could be clearly observed as well. These observations indicate that calibrating ply thicknesses is not a good idea since the actual configuration is impossible to predict and can differ from one specimen to another. The total masses and dimensions were accurately determined (used to verify the material density) and the plate curvatures were measured (no significant influence).

5.2 Model Calibration

FE model updating is considered an important part of the model validation and verification process [12]. The difference between normal mode analysis results (subjected to design parameter variation) and experimental results is measured by an objective function that is subsequently optimized in order to find a set of design parameters that improves the match between analytical model and test data.

A very close match between the FE model and test results for all specimens could only be achieved with significant changes to either the material properties or the ply thicknesses that were deemed unacceptable by the project. Also, one set of material properties that was optimal for one test object did not improve results for another. As a consequence, it was decided for this project to settle for a slight calibration of the laminate material properties that was well inside the variability found during material testing, consisting of a 3% change from the original values, which corresponds to about 1/3 of the observed range of values during material testing. An update that we performed on the open Z-profile, and then consistently applied to the quasi-isotropic, the uni-directional, and the closed double-Z-profile improved correlation results by an average of about 1% to 2% from the original baseline.

6 Conclusions

A systematic approach to the validation of laminate structures modeled in Nastran with shells and composite properties (PCOMP) for automotive applications was presented. The approach proved successful for laminate panels and assemblies of two parts featuring relatively simple geometries.

The key concepts of the approach were summarized, including steps taken to maximize chances of a positive outcome, such as the suitable design of the test structures, preparation of the modal tests, and in-depth sensitivity analyses.

FE model correlation was carried out for all specimens, and the agreement between test and simulation results was found to be good. In particular, the final project objective, a closed double-Z-profile, was successfully validated with a low average frequency error of about 2% for the fundamental modes in the objective frequency range of up to 1000 Hz.

Further studies were conducted after the tests in order to better understand the results. Insight was provided into the main influences on the fundamental modal properties of the tested structures. For the structures examined, these included ply thicknesses (in the case of plates, in particular the outer plies); to some extend, E1 and G12 of the laminate material properties; correctness of the global material orientation of quasi-isotropic laminates, as opposed to local ply angles. Influence of the material properties of the particular stiff, structural adhesive that was used for the closed double-Z-profile was found to be very low.

Finally, model calibration was performed by slightly adjusting the laminate material properties; this resulted in a small improvement of the correlation results by about 1% to 2%.

Future work will deal with more complex automotive laminate structures as well as fiber reinforced plastic composites produced by other manufacturing processes. Further validation studies on different types of adhesives between laminate parts should also be done in the future.

7 Acknowledgment

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8 References

[1] Chamis, C. C., Sinclair, J. H., Sullivan, T. L., "NASTRAN as an Analytical Research Tool for Composite Mechanics and Composite Structures", NASTRAN: Users' Experience, pp. 381-418, October, 1976, (NASA TM X-3428).

[2] Wilt, J. C., "Use of Composite Materials in NASTRAN", AIAA/ ASME/ASCE/AHS 24th Structures, Structural Dynamics and Materials Conference, part 1, pp. 612-622, May, 1983.

[3] Ramsay, A., "Evaluation of NASTRAN Elements in the Analysis of Fibre-Reinforced Composites", Proc. of the MSC/NASTRAN European Users' Conference, April, 1982, paper 12.

[4] Narayanaswami, R., Cole, J. G., "Layered Composite Analysis Capability for NASTRAN", Thirteenth NASTRAN Users' Colloq., pp. 67-109, May, 1985, (NASA CP-2373).

[5] Nagendra, G. K., Fleury, C., "Sensitivity and Optimization of Composite Structures Using MSC/NASTRAN, MSC/NASTRAN Users' Conference, paper 20, March, 1986.

[6] Hemez, F.M., Tippetts, T.B., "Verification and Validation of a Composite Model", draft report of the Los Alamos LDRD-DR "Damage Prognosis" project, November 2004.

[7] Napolitano, K.L., Blelloch, P.A., "Automated Selection of Shaker Locations for Modal Tests", 21st. International Modal Analysis Conference on Structural Dynamics, Kissimmee, FL, 02, 2003.

[8] Ewins, D.J., "Modal Testing: Theory, Practice and Application", Second Edition, Research Studies Press Ltd., Baldock, England, 2000.

[9] He, J. and Fu, Z.F., "Modal Analysis", Butterworth-Heinemann, 2001.

[10] Allemang, R.J., "The Modal Assurance Criterion — Twenty Years of Use and Abuse", Journal of Sound and Vibration, August 2003.

[11] Mukhopadhyay, M., "Mechanics of Composite Materials and Structures", Universities Press, 2004.

[12] Friswell, M.I., Mottershead, J.E., "Finite Element Model Updating in Structural Dynamics", Kluwer, 1995.