DAMAGE DETECTION IN CARBON FIBER FILAMENT WINDING CYLINDERS

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Abstract

The structural health monitoring (SHM) systems can improve even more the application of composite materials in aircraft structures. This study presents finite element analyses in order to determine health monitoring metrics and techniques for detection, localization and sizing the damage in carbon fiber filament winding cylinders. A finite element software ABAQUS^{TM} was used to perform the electro-mechanical analyses. First, natural frequencies and modal parameters (frequency response function, FRF) were obtained for undamaged cylinder model with piezoelectric patches sensors. Second, the structure was hit by an impactor and the damage was calculated by a material model. Third, the natural frequencies and FRF for the damaged model were extracted and compared with undamaged model results. The results show that the techniques and metrics allow identify the presence of damage.

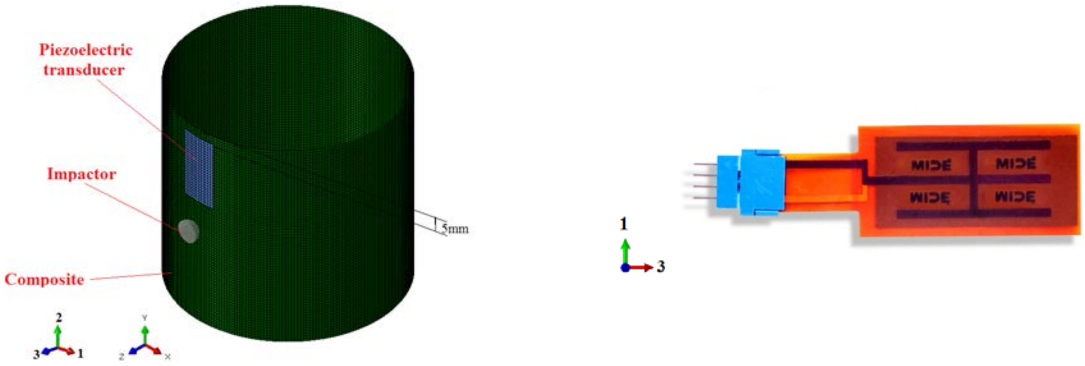
1 Introduction

The application of composite materials in aeronautical industry have been increasing in the last decades, even in large civil transportation aircrafts, mostly due to composite high stiffness and low weight [1]. Its intrinsic anisotropy allows achieve an optimal material performance, regarding the structure geometry and applied loadings. Composite materials can provide lighter structures without loss of airworthiness, which is a very attractive characteristic for aeronautical industry. However, it is well know how the inspection affects the maintenance costs. Thus the maintenance program must be well planned, but predictions of the inspections are hard task, mostly for composite structures. Because, unexpected loads could affect the structural integrity, changing the original maintenance plan and, the damage processes for composite materials are more complex than for metals. For example, intra-ply failures and delamination could occur [2], reducing the structural strength. These types of damages can be caused by low velocity impact. There are several sources of low velocity impact, such as dropping tool, debris, etc. [3], which causes damage in the structure. However, the damage is dependent of the geometry, laminate thickness, stacking sequence, energy level and boundary conditions [4]. Therefore, several studies of composite plates impacted were conducted by different researchers ([5], [6]), but only few studies were made regarding impact in curved geometry ([7], [8]). Despite the high strength in fiber direction, out-of-plane loads, for example impact loads due to bird strike or dropping tool in a composite structure, could lead to severe damage. In a metallic structure this kind of damage is easier to detect, on the other hand for carbon fiber structures, it is more complicated [7]. Regarding the previous commented issues, the structural health monitoring (SHM) techniques arise as viable solution to reduce the inspections and to optimize the structural maintenance program, performing the repair only when it is necessary, reducing the operational costs. For composite structures, it is possible to laminate the structure inserting piezoelectric sensors to detect and measured the damage. Thus, there are several works about SHM in the literature. Rytter [9] defined four levels to evaluate a damage in a structure. Other researchers ([10], [11], [12]) also investigated life in service and system reliability, using SHM systems, which are composed by methods to detect, localize and quantify the structural damage. Farrar and Doebling [13] performed a review of some methods, which assess the vibration response in order to detect, localize and quantify the structural damage. In fact, those methods use the differences in natural frequencies and modes between the undamaged and damaged structure due to modifications of the structural stiffness, mass and damping for monitoring the structure.

The present work performs SHM analyses of filament winding cylinder damaged by impact load, using piezoelectric patches. First, frequency analyses of undamaged cylinder were performed. Second, Progressive Failure Analyses (PFA) were carried out for the cylinder under low energy impact load. During the impact simulations, the damage was calculated by a new material model [14] implemented as a FORTRAN subroutine (UMAT), which was linked to the finite element program ABAQUS^{TM}. After the impact simulation, frequency analyses of damaged cylinder were carried out and compared with undamaged model results. Finally, the results shows that the techniques and metrics allow identify the presence of damage.

2 Composite cylinder and piezoelectric transducer

The cylinders in composite material has a piezoelectric transducer bonded on the outer surface (*cf.* Figure 1a). The composite cylinders are made of fourteen layers, stacked $[90/60/-60/90/60/-60/90]_s$ with the following geometries: outer diameter 163.7 mm, length 150 mm and total thickness of 3.4 mm. The piezoelectric transducer (Midé QP10n, *cf.* Figure 1b) has the following geometry: length 50.8 mm, width 25.4 mm and thickness 0.5 mm. In order to facilitate the development of finite element models, they were obtained through subroutines in Python, which are performed by the program ABAQUS^{TM}. The composite cylinder properties were obtained by Ribeiro et al. [14] and the piezoelectric transducer properties were obtained by Medeiros [15].



(a) (b)

Figure 1: (a) Finite element model: composite cylinder with the piezoelectric transducer bonded on the outer surface; (b) Piezoelectric transducers Midé QP10n.

It is noteworthy that for the composite material, the local coordinate system (1-2-3) is defined by the fiber reinforcement, *i.e.*, 1-direction is aligned with the reinforcement, the 2-direction is normal to the reinforcing and 3-direction is normal to the plane of the layer. However, for the piezoelectric transducer, which has 3-direction (local coordinate system) is related to the longitudinal direction of the insert, and 1- and 2-directions are related to the direction of the cross section of the insert. Therefore, it appears that the polarization direction is aligned with the 3-direction of the piezoelectric transducer.

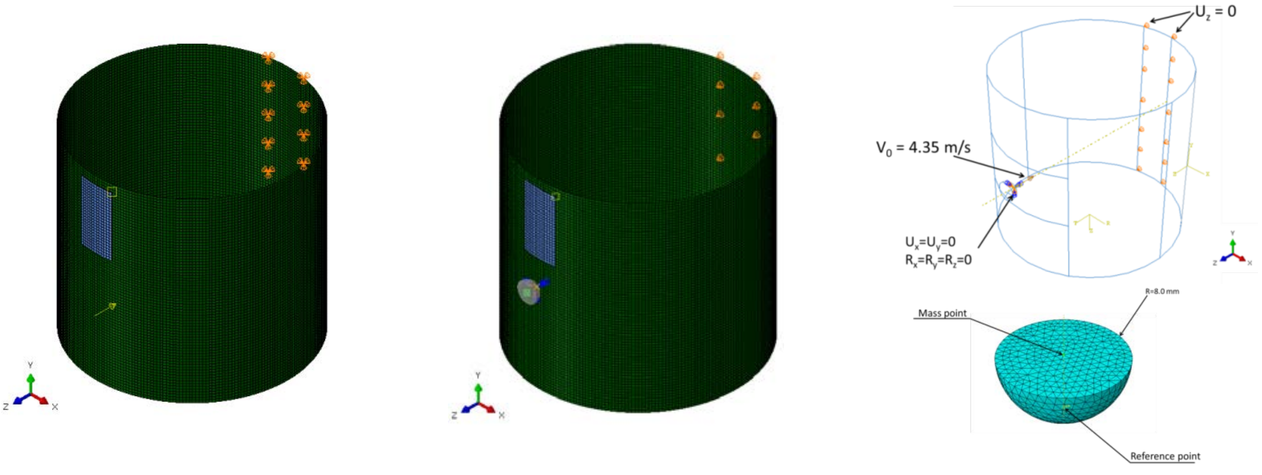
Another important aspect of finite element model is to ensure the mechanical coupling between the cylinder and the piezoelectric transducer. Once assured that mechanical coupling, it is necessary to define appropriate conditions for reading the electric potential in the patch transducer. Naturally, the dielectric properties of the Midé QP10n prevent the homogeneous distribution of the induced electrical charges on the free surface of the patche. Two electrical boundary conditions can be considered: 1) open-circuit (OC) and 2) short-circuit (SC). For case 1, all the nodes of the piezoelectric patche surface bonded to the cylinder are considered electrically grounded and the free surface respect to equipotential condition. For case 2, the nodes of the base and top are grounded, so that the electrical potentials at the top and bottom of each insert are invariably and maintained constant. The patche behaves as a short-circuit device. Physically, the generated surface charges are disposed outside the transducer by conductive wires in order to keep it discharged [16].

In order to proceed with the investigation of how the damage evolves in composite cylinders under impact loads, the present work uses a new damage model proposed by Ribeiro et al. [14], which is linked to the finite element dynamic implicit algorithms (ABAQUS/Implicit).

This model is simple to be implemented and has a low computational cost, which makes it suitable to simulate complex finite element models. Also, the model parameters are easy to be obtained (as shown by Ribeiro et al. [14]).

3 Finite element model and numerical analyses

A four node reduced integration shell element with six degree of freedom (DOF) per node (S4R) were used to model the cylinder. Nevertheless, when performing a PFA, some elements could become excessively distorted, aborting the analysis. In order to overcome this issue, the mesh was refined until the severe element distortion was eliminated. The piezoelectric patche is modeled using eight-node coupled plane elements (C3D8E), with four DOF per node, which are the displacements in x, y and z directions and the electric voltage. Therefore, measurement of the electric potential in a specific node on the free surface will correspond to local information under an applied strain. In practice, the free surface of each patch is covered with an electrode, which ensures a uniform level of induced electric potential (equipotential) in the free surface of each patch. To ensure an ideal perfect bonding between the piezoelectric patche and the cylinder, the nodes on the bottom surface of the patch is mechanically coupled to the ones on the top surface of the cylinder. The grounding nodes of the piezoelectric surfaces bonding with the cylinder are accomplished by requiring the potential is zero at any stage of srain. The purpose of grounding is to define a reference value in relation to which the voltages induced on the nodes of the free surface are measured.



(a) (b) (c)

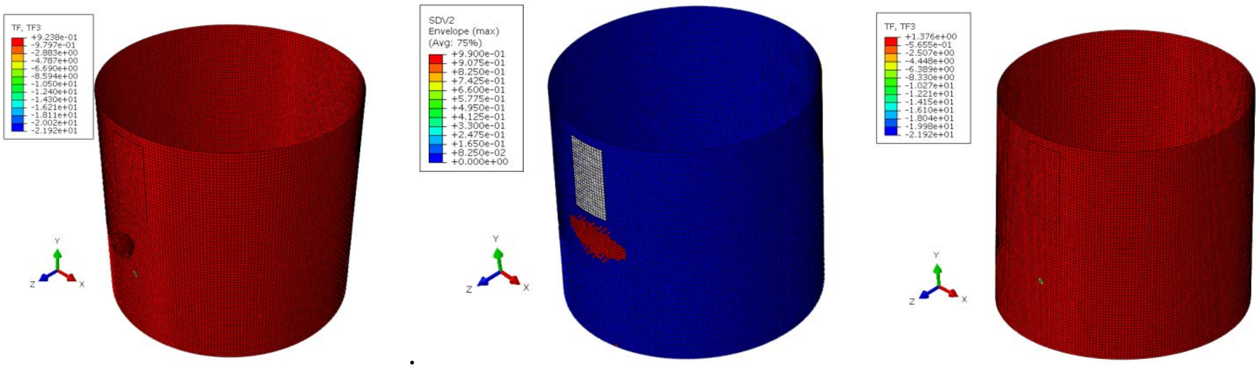
Figure 2: (a) Boundary conditions for frequency response of the structure before and after impact; (b) Boundary conditions for impact analysis; (c) Finite element model geometry and impactor mesh.

The first numerical simulation consists on performing modal analysis of the undamaged cylinder (*cf.* Figure 2a). The second numerical simulation consists on the impact analysis of the cylinder where the damage was calculated using the material model commented earlier [14] (*cf.* Figure 2b). The boundary condition for impact simulations is used in order to simulate a V-base. The impactor is modeled using discrete rigid triangular elements (R3D3). The point mass of 3.24 Kg is applied in the mass point. Also, all rotations (R_x, R_y, R_z) as well as the U_x and U_y are restricted. Initial velocity of 4.35 m/s is applied in the impactor (*cf.* Figure 2c). The contact between the impactor and the cylinder were modeled as hard contact for normal behavior and penalty for tangential behavior. Other important issue in simulating of the the impact in composite filament winding cylinders is the dissipation of the impact energy. Part of the impact energy is dissipated by irreversible process as damage (intra-ply failures and delaminations), other part is dissipated by damping effects. However, damping in composite materials are dependent of several factors as fiber volume fraction, composite lay-up, environmental factors, force magnitude, etc. [16]. Also, the structure geometry has an important influence in the impact response. ABAQUS^{TM} provides the Rayleigth's model for direct integration dynamic analysis in order to simulate energy dissipation mechanisms [17]. The Rayleigth's model introduces damping in the structure as a linear combination of mass and stiffness system matrices [18]. In finite element analysis, damping is treated as a matrix that opposes the excitation. Damping can be treated in two different ways, as a material property or as a numerical object to oppose the excitation [18].

The third numerical simulation consists on performing modal analyses for damaged cylinder, obtained from the impact analyses, described earlier. Thus, a harmonic loading was applied on top of the cylinder located to the left of piezoelectric transducer (Figure 1a), simulating the excitation of a shaker. Such harmonic input is a transverse force like sine with amplitude equal 100N concentrated in a node located at the top (Figure 2a). The frequency of the sinusoidal force is discretized in the range 0-100 Hz. Also, the nodes belonging to the line of contact with the base of the cylinder (Figure 2a) have been clamped. It should be noted that these boundary conditions and loading were applied to both intact and damaged cylinder.

4 Results

Several metrics can be used for damage detection, localization and quantification. This work makes use of frequency response function. Regarding the transfer function response methods, the differences between the damaged and undamaged structures were compared and then the differences indicate the damaged. This method is easier to be implemented and also gives a good prediction of the structural integrity [19]. The open-circuit electrical boundary condition is the condition for the final structural modeling and it obtains the FRFs from the modal and harmonic analysis. Considering that the result is null i.e. the two tablets in SC. It is noteworthy that models of the cylinder clamped in two lines along the length with piezoelectric inserts bonded presents linear response to steady state sinusoidal inputs. For each excitation frequency, there is a typical configuration of elastic deformation in the structure, hence a uniform distribution of the voltage induced in the equipotential surface of each piezoelectric wafer. The absolute value of the voltage induced in each sensor depends on the degree of elastic strain to which it is subjected. In general, the maximum voltage amplitude of each sensor are associated with strains caused by some modes of the structure vibration, which occurs for excitation frequencies sufficiently close to the respective natural frequencies. Figure 3 shows the results for the undamaged cylinder, the impacted cylinder (damaged area), and for damage cylinder. Moreover the Figure 4 shows the frequency function response for damage and undamaged cylinder.



(a) (b) (c)

Figure 3: (a) Cylinder undamaged - harmonic loading for FRF analyses; (b) Cylinder after impact – damage zone; (c) Cylinder damaged - harmonic loading for FRF analyses.

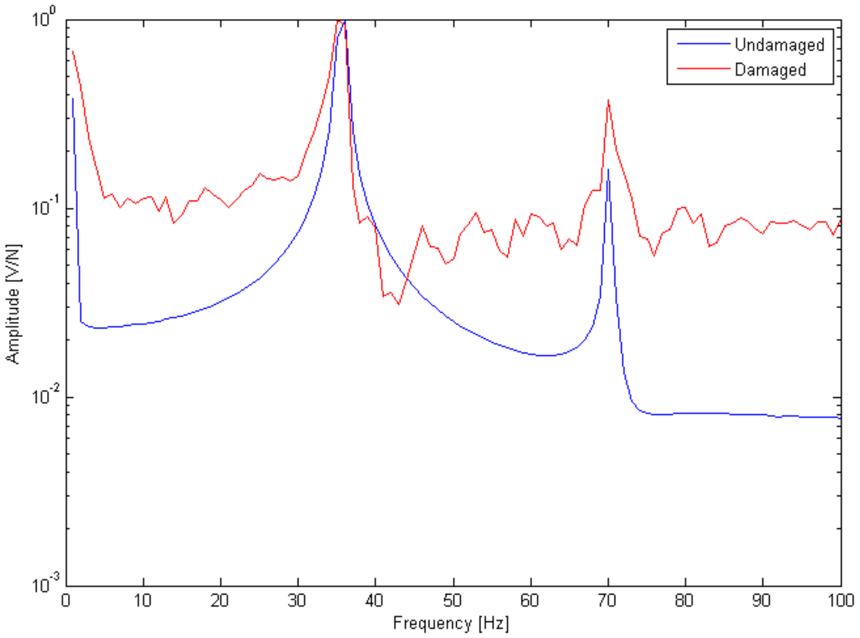


Figure 4: FRF using piezoelectric patche: cylinder intact vs. damaged cylinder

There are many advantages in employing the method based on FRFs in a SHM system. Among these advantages, it can be easily implemented and has low cost. Also can be light and provide a good predition of the overall integrity of the structure. On the other hand, there are limitations, since they provide little information about the damage site, unless large amounts of sensors are employed.

5 Conclusions

Based on these results, it is concluded that the application of metrics based the FRFs for detecting damage to a cylinder of composite material is feasible since there are changes overall rigidity and therefore relatively large damage. Numerical models showed intact and damaged, and this conclusion is presented as an alternative to evaluate SHM systems. Furthermore, the results indicate a severe limitation of existing methods is the lack of information about the location or type of damages. Therefore, these methods are suitable for a system SHM, which allows simply identifying the presence or otherwise damaging the structure.

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7 References

[1] K.V. Williams, R. Vaziri, and A. Poursartip, "A physically based continuum damage mechanics model for thin laminated composite structures," *International Journal of Solids and Structures*, vol. 40, no. 9, pp. 2267-2300, 2003.

[2] V. Tita, J. de Carvalho and D. Vandepitte, "Failure analysis of low velocity impact on thin composite laminates: Experimental and numerical approaches," *Composite Structures*, vol. 83, no. 4, pp. 413-428, 2008.

[3] G.A. Schoeppner and S. Abrate, "Delamination threshold loads for low velocity impact on composite laminates," *Composites Part A: Applied Science and Manufacturing*, vol. 31, no. 9, pp. 903-915, 2000.

[4] ASTM, *D7136/D7136M Standard Test Method for Measuring the Damage Resistance of a Fiber-Reinforced Polymer Matrix Composite to a Drop-Weight Impact Event.*, 2007.

[5] S.M.R. Khalili, M. Soroush, A. Davar and O. Rahmani, "Finite element modeling of low-velocity impact on laminated composite plates and cylindrical shells," *Composite Structures*, vol. 93, no. 5, pp. 1363-1375, apr 2011.

[6] X. Xiao, "Evaluation of a composite damage constitutive model for PP composites," *Composite Structures*, vol. 79, no. 2, pp. 163-173, 2007.

[7] L. Ballère, P. Viot, J.-L. Lataillade, L. Guillaumat and S. Cloutet, "Damage tolerance of impacted curved panels," *International Journal of Impact Engineering*, vol. 36, no. 2, pp. 243-253, 2009.

[8] S. Kobayashi and M. Kawahara, "Effects of stacking thickness on the damage behavior in CFRP composite cylinders subjected to out-of-plane loading," *Composites Part A: Applied Science and Manufacturing*, vol. 43, no. 1, pp. 231-237, 2012.

[9] A. Rytter, "Vibration Based Inspection of Civil Engineering Structures," Aalborg, Denmark: Aalborg University, 1993.

[10] J. Wallaschek, S. Wedman and W. Wickord, "Lifetime observer: An application of mechatronics in vehicle technology," *International Journal of Vehicle Design*, vol. 28, no. 1-3, pp. 121-130, 2002.

[11] K. Wolters and D. Söffker, "Control of Damage Dependent Online Reliability Characteristics to Extend System Utilization," *Proc. 4th Intl. Workshop on Structural Health Monitoring*, 2003.

[12] D.E. Adams, "Health Monitoring of Structural Materials and Components Methods with Applications", The Atrium, Southern Gate, Chichester, West Sussex , England: John Wiley & Sons Ltd, 2007.

[13] C.R. Farrar and S.W. Doebling, "An Overview of Modal-Based Damage Identification Methods," in *Proceedings of DAMAS Conference,* Sheffield, 1997.

[14] M.L. Ribeiro, V. Tita, and D. Vandepitte, "A new damage model for composite laminates," *Composite Structures*, vol. 94, no. 2, pp. 635-642, 2012.

[15] R. Medeiros, "Development of a Computational Methodology for Determining Effective Coefficients of the Smart Composites," Dissertation (Master of Science) – School of Engineering of São Carlos, University of São Paulo, São Carlos, SP, Brazil, 2012, (in portuguese).

[16] N. Zabaras and T. Pervez, "Viscous damping approximation of laminated anisotropic composite plates using the finite element method," *Computer Methods in Applied Mechanics and Engineering*, vol. 81, no. 3, pp. 291-316, 1990.

[17] Dassault Systèmes Simulia Corp, *Abaqus 6.10*. Providence, RI, USA., 2010.

[18] C. Kyriazoglou and F.J. Guild, "Finite element prediction of damping of composite GFRP and CFRP laminates a hybrid formulation vibration damping experiments and Rayleigh damping," *Composites Science and Technology*, vol. 67, no. 11-12, pp. 2643-2654, 2007.

[19] M.A. Trindade and A. Benjeddou, "Effective Electromechanical Coupling Coefficients of Piezoelectric Adaptive Structures: Critical Evaluation and Optimization," *Mechanics of Advanced Materials and Structures*, vol. 16, pp. 210-223, 2009.

[20] C.C. Pagani Jr, "Design and optimization of modal filters using arrays of piezoelectric sensors," Master´s dissertation – São Carlos School of Engineering, University of São Paulo, São Carlos, 2009 (in portuguese).

[21] S.S. Kessler, S. M. Spearing, M. J. Atalla, C.E.S. Cesnik and C. Soutis, "Damage detection in composite materials using frequency response methods," *Composites Part B-Engineering*, vol. 33, no. 1, pp. 87-95, 2002.