

Vibration-based Structural Health Monitoring of composite structures

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Abstract: Vibration-based Structural Health Monitoring (SHM) is a method to assess damage in structures, working in the principle that variations on the stiffness, mass or energy dissipation properties of the structure will alter its dynamic response (e.g., mode shapes and natural frequencies). Composite laminate and sandwich structures are more often used in aircraft components. Composite damage features peculiar mechanisms, the most relevant being layer delamination in laminates, skin debonding in sandwich constructions and composite penetration. Delamination and debonding may be internal to the structure and not visible externally render difficult their assessment. These damage mechanisms will change the dynamic response of the structure that may be used to identify damage. In this way, vibration-based SHM is a potential method for damage assessment in composite structures. In this work the feasibility of a vibration based damage identification method in composite structures will be explored through FEA simulations in Abaqus. Several damage scenarios are simulated and the dynamic response of the composite evaluated. Various existing models of damage in laminated composite and the resulting stiffness degradation are discussed. Results post-processing operations are performed using a specially developed signal processing tool that, within Abaqus platform, maximizes the efficiency of post-processing operations in time and frequency domains.

Keywords: Delamination, Cohesive elements, Dynamic response, Structural Health Monitoring.

1. Introduction

Vibration-based Structural Health Monitoring, SHM, methods are based on the dynamic response of structures. A change on the dynamic response (considering constant the boundary conditions) of a structure implies modifications relative to a healthy structure due to a change on material properties. In fact, the dynamic response of a structure is dependent on several material parameters, such as density, stiffness and damping, which has a direct effect on the dynamic response of the structure (Kim H-Y, 2003).

In service damages of composite can be originated from several causes:

- i) In service mechanical loading, such as excessive static loads, vibrations, fatigue or creep;
- ii) Accidental loadings, such as impact/shock of falling weights or lightning strikes;
- iii) Environmental cycling loadings, such as temperature and humidity;
- iv) Environment attacks causing bacterial/chemical degradation or galvanic corrosion.

All these factors, isolated or combined, induced diverse types of damages in the composite structures, namely:

- a) fibre related (fracture, debonding);
- b) matrix related (cracking);
- c) surface defects on skins (dents, abrasions, scratches, punctures);
- d) full or partial penetration of the composite.
- e) delaminations or debonds in laminated composites;
- f) skin/core delamination in sandwich constructions;
- g) core crushing in sandwich constructions;
- h) in adhesive joints

Delaminations in composite laminates and skin/core debonding in sandwich constructions are most common type of damages. Moreover, as they can be internal to the composite they are not externally visible, render rather difficult their identification. Non-destructive testing, NDT, methods are widely used for damage identification in composite materials. (R. Unnþórsson et. al., 2004)

In the manufacturing of aeronautic components, the joining of parts has been done more efficiently by adhesive joints rather than by mechanical coupling (e.g., bolts, rivets). The evaluation of the integrity status of the bonded joint is of primordial relevance as it affects the mechanical response of the structure. Bonded joint performance is influence by in-service conditions and associated damage mechanisms. The origin of weakness of adhesive joints can be grouped in (C. Cao et. al., 2003):

- i. in service damage (e.g., aging, impact, fatigue, creep, environmental degradation);
- ii. physical discontinuities in bond (e.g., void, inclusions, contaminations, cracks);
- iii. weak adhesive (e.g., manufacturing problems, internal stresses);
- iv. poor adhesion (ineffective surfaces preparation or contaminations).
- v. In service mechanical loading, such as excessive static loads, vibrations, fatigue or creep;

These causes induced diverse types of damages in the composite-to-composite adhesive bonds, the main ones being:

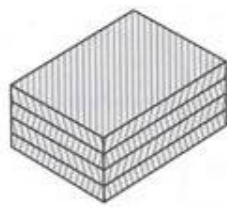
- a) composite failure (failure within the adherend);
- b) adhesive or interfacial failure (between adhesive and adherend interface);

- c) cohesive failure (cracks propagate within the bond).

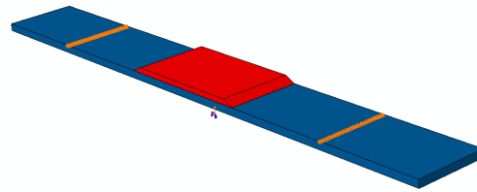
Interlaminar damage (delamination) is one of the most predominant types of failure in composite structures (in ply-laminates, sandwich constructions or adhesive joints). Delamination is a process that causes changes in the dynamic response of the structure and consequently it can be detected from vibration-based SHM methods. This process causes a decrease on the structural stiffness that must be captured early in order to avoid a catastrophic collapse of the structure. Detection of damage in composite materials using frequency response methods has been reported (Kim H-Y, 2003; Kessler SS et. al., 2002; Whittingham B et. al., 2006). The extent of damage has been related to the reduction in natural frequency mainly at high frequencies, but it was argued that the specific location and type of damage is difficult to achieve by frequency response methods alone (C. Cao et. al., 2003). For a free vibrating rectangular plate, its natural frequencies (mode 1) decreases with the increment of the delamination length and of the plate aspect ratio; but mode 2 frequency depends, besides on the aspect ratio, also upon the delamination position (Shiau L-C et. al., 2010). Internal delaminations in composites are more difficult to identify by frequency response methods, and normally higher frequencies are normally required (Whittingham B et. al., 2006). It is well established that the reduction of the natural frequencies or the increment upon damping in delaminated composites are related to the dimension and location of damage (Zou Y et. al., 2000). Furthermore, the maximum frequency shift occurs for modes with the wavelength of the same size of the delaminated area (Paolozzi A. et. al., 1996). In general, the damping coefficient is more sensitive to delamination than changes on the stiffness (Zou Y et. al., 2000). Delamination changes the frequency response of adhesive joint composites that decreases in magnitude and frequency position (Caleb White et. al., 2009). Vibrations methods have been used for monitoring delaminations in advanced composites components, being them evidenced as useful tools for SHM methods.

Finite Element Analysis, FEA, can contribute to estimate the relative change of dynamic response between a healthy structure and a delaminated composite structure allowing the definition of several damage scenarios. In this approach, interfacial cohesive elements can be used in order to model the interfacial mechanical response of composites structures (such as cross-ply laminates and sandwich constructions) (Camanho P.P. et. al., 2002). These elements are suitable to model the mechanical behavior and integrity of composite interfaces and predict the stiffness degradation associated with the delamination processes. Very good correlations between experimental and simulated vibration spectra data is found for simple geometries (e.g., bars, beams) (Kessler SS et. al., 2002). Studies on simulations of vibrations of two-dimensional geometries finite plates are scarce (Shiau L-C et. al., 2010). However, for more complex geometries (e.g., stiffened composite panels) a substantial deterioration on this agreement is obtained (Loendersloot R. et. al., 2010)

In this work, mode-based and implicit dynamic simulations are defined to extract the dynamic response of healthy and delaminated composite structures (Figure 1) considering 2D and 3D geometries for different loading cases. Cohesive elements were used to simulated interfacial properties. Different damage levels were induced by static loading at distinct strains ranges. Then the vibration behaviour of the damaged composite structures were simulated and compared.



a) Ply-laminate composite



b) Adhesive joint composite

Figure 1 – Type of composite structures studied.

2. SHM – Structural Health Monitoring

SHM aims to give, at every moment during the useful life of a structure or its components, a diagnosis and prognosis of the structural condition of the constituent materials. The state of the structure must remain in the domain specified by design, although this can be altered by normal aging due to usage, by the action of the environment, and by accidental events. The SHM system must also deal with the consequences at material level of such events. The knowledge of the integrity of in-service structures of critical systems on a continuous real-time basis, thus supporting effective decision-making actions at various levels of the system life-cycle (e.g., maintenance, part replacement, logistics, mission planning) is a clear asset for manufacturers, end-users and maintenance teams, in several industrial sectors (most relevant being: transportation system - aerospace, surface transports; defense; energy - wind power, nuclear stations; infrastructures).

A highly effective and reliable SHM system must be designed with emphasis on developing a low complexity solution and this objective is only attainable with a radical reduction of the number of sensors attached to the structure/component. In the actual SHM systems, a drastic reduction of sensors implies a low resolution mapping of the monitored variables and, consequently, a weakness on the diagnosis and prognosis of the structure condition. Therefore, the developing of a complementary computational strategy permitting the virtualization of the representative geometry and the physics of the structural system is of paramount importance. These simulations are obviously relevant at the structure/component design stage, but also at its operation phase, as they can synergistically support advanced SHM systems. In this work it is shown this approach, where the simulation of the frequency response of advanced healthy and damaged composite structures are performed using Abaqus code. The existence of such knowledge and expertise is essential for the development of the next generation of advanced SHM systems.

3. WorkFlow

In Figure 2 is summarized the workflow followed in this work. The effect of delamination on the structural stiffness and its influence on the dynamic response of the structure was studied using 2D and 3D models enriched with cohesive elements in the interfaces. The level of delamination was controlled via a static displacement step. The static step was followed by a modal steady-state dynamics procedure for tracking changes in the dynamic response of a delaminated structure when compared with a healthy one.

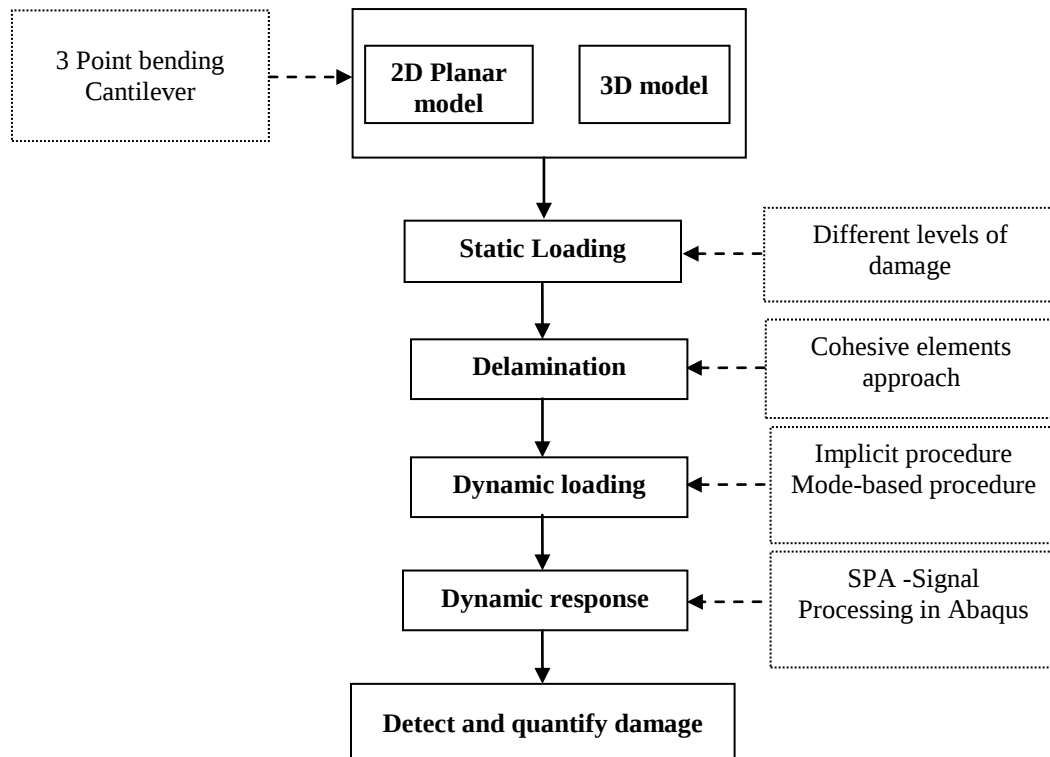


Figure 2 - Workflow followed in this work.

4. FE Models

4.1 FE model (2D)

A cantilever beam was modeled in a 2D plain strain state considering a laminate composed of 5 plies with 0.75 mm of thickness each. The 4 interfacial regions were defined with 2D cohesive elements (COH2D4), considering a 0.075mm thickness, and the material plies were discretized using 2D plain strain quadratic elements (CPE8R).

4.1.1 Material properties

The constitutive response of cohesive elements was defined via traction-separation approach with interface mechanical properties displayed in Table 1 (Camanho, P.P. et. al., 2004). The damage evolution criterion was based on the Benzeggagh-Kenane model (Equation 1) and the damage initiation criteria based on the maximum nominal stress criterion

$$G_{IC} + (G_{IIC} - G_{IC}) \left\{ \frac{G_{II}}{G_I} \right\}^\eta = G_C \quad (1)$$

In Equation 1, G_{IC} and G_{IIC} correspond to the critical strain energy release rate in the normal and tangential direction, respectively, G_{II} and G_I are the actual fracture energy in the normal and tangential directions, respectively, G_C is the energy dissipated due to failure, and η is a material parameter.

For the maximum stress criterion, damage is assumed to trigger when the maximum nominal stress ratio (as defined in Equation 2) reaches the value of one.

$$\max \left\{ \frac{\langle t_n \rangle}{t_n^0}, \frac{t_s}{t_s^0}, \frac{t_t}{t_t^0} \right\} = 1 \quad (2)$$

In equation 2, t_n^0 is the maximum nominal tensile strength, and t_s^0 and t_t^0 are the maximum nominal shear strength in direction 1 and 2, respectively.

Table 2 resumes the ply orthotropic material properties (AS4/PEEK carbon fiber reinforced composite). (Camanho, P.P. et. al., 2004)

Table 1. Interface mechanical properties (Camanho, P.P. et. al., 2004).

G_{IC}	G_{IIC}	t_n^0	t_s^0	η
0.969 N/mm	1.719 N/mm	80 MPa	100 MPa	2.28

Table 2. Ply material properties (Camanho, P.P. et. al., 2004)

E_{11}	$E_{22}=E_{33}$	$\nu_{12}=\nu_{13}$	ν_{23}	$G_{12}=G_{13}$	G_{23}
122.7 GPa	10.1 GPa	0.25	0.45	5.5 GPa	3.7 GPa

In Table 2, E_{11} , E_{22} and E_{33} are the Young modulus in the respective directions, G_{12} , G_{13} and G_{23} correspond to the transversal moduli and ν_{12} , ν_{13} and ν_{23} are Poisson's ratios in the respective planes.

4.1.2 Induced damage by static loading

A static displacement is imposed at the beam tip in order to induce delimitation of the laminate structure. A subsequent mode-based steady state is defined with a dynamic load (considered constant through the considered frequency range) imposed near the beam clamping zone, as depicted in Figure 3. After the delamination step the component returns to its initial position (but maintaining its internal damage), before the definition of dynamic loading procedures.

Two levels of static displacement were considered in order to obtain different levels of delamination in the cohesive zone.



Figure 3. FE 2D planar model (cantilever beam).

4.2 FE model (3D)

A large number of aerospace structures are made from composite panels whose structural stiffness is increased through the inclusion of adhesively bonded frames or stiffeners. Normally, these bonded structures are more susceptible to delamination and fracture that could lead to a structural catastrophic failure. In this work, the delamination of a skin-flange subjected to a three-point bending test was considered. Figure 4 shows the considered 3D model. The cohesive region is defined at the interface skin/stiffener with a correspondent thickness equal to 7.5×10^{-3} mm.

The cohesive regions were discretized using 3D cohesive elements (COH3D8), while the mesh domains of skin and flange components were defined using linear hexahedron elements (C3D8I).

Like in the previous 2D model, a static loading procedure was considered for the assessment of interfacial delamination, followed by a mode base steady-state analysis procedure for the simulation of the structural dynamic response.

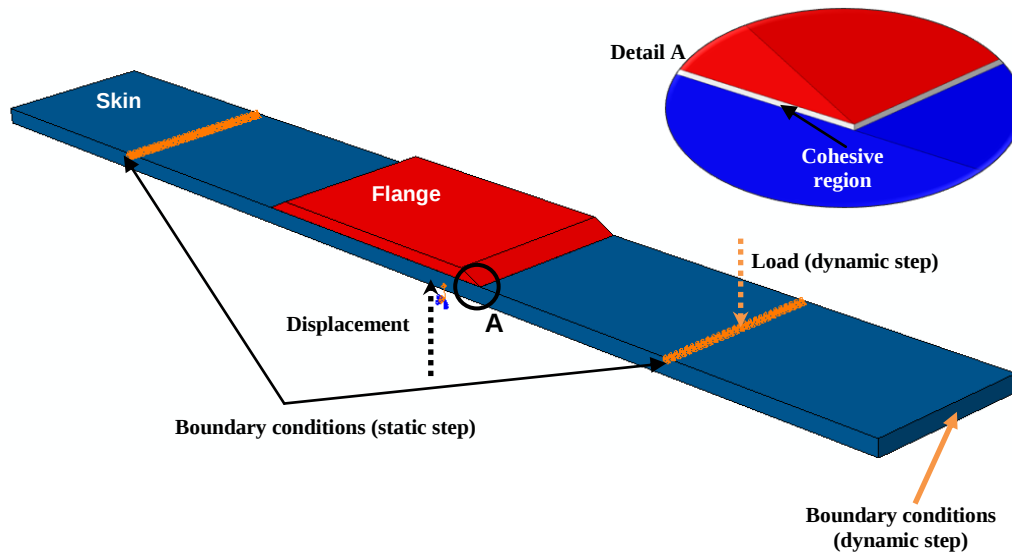


Figure 4. Skin-Stiffener 3D model.

4.2.1 Material properties

Interfacial material properties used for the definition of the cohesive region are listed in Table 3. A traction-separation approach was considered with penalty stiffness equal to 1×10^6 N/mm³. The damage evolution (considered linear) criterion was based on the Benzeggagh-Kenane energy model and the damage initiation criteria based on the maximum nominal stress criterion (MAXSCRT). In Table 4 are summarized the orthotropic material properties (IM6/3501-6 graphite/epoxy prepreg) of skin and flange.

Table 3. Interface mechanical properties (Camanho, P.P. et. al., 2004).

G_{IC}	G_{IIC}	t_n^0	t_s^0	η
0.075 N/mm	0.547 N/mm	61 MPa	68 MPa	1.45

Table 4. Ply material properties (Camanho, P.P. et. al., 2004).

E_{11}	$E_{22}=E_{33}$	$\nu_{12}=\nu_{13}$	ν_{23}	$G_{12}=G_{13}$	G_{23}
144.7 GPa	9.65 GPa	0.3	0.45	5.2 GPa	3.4 GPa

4.2.2 Induced damage by static loading

Delamination of the skin-stiffener interface is achieved through the definition of a three point bending static case (Figure 4). A normal-to-the-surface displacement is applied through a multipoint constrain at the midspan of the skin component. After the delamination static step, the component returns to its initial position before the definition of dynamic loading procedures. A subsequent mode-based steady state procedure is defined considering a dynamic load imposed near the skin clamping zone (Figure 4). For the dynamic mode-based simulation procedure the component was considered as being loaded in cantilever mode.

5. Results

5.1 2D Model

For the considered imposed displacements the initiation of damage was obtained near the clamped boundary condition, considering the Maximum Nominal Stress Criterion (MAXSCRT) (Figure 5). In Figure 6 is visible the correspondent interfacial stiffness degradation in the cohesive region.

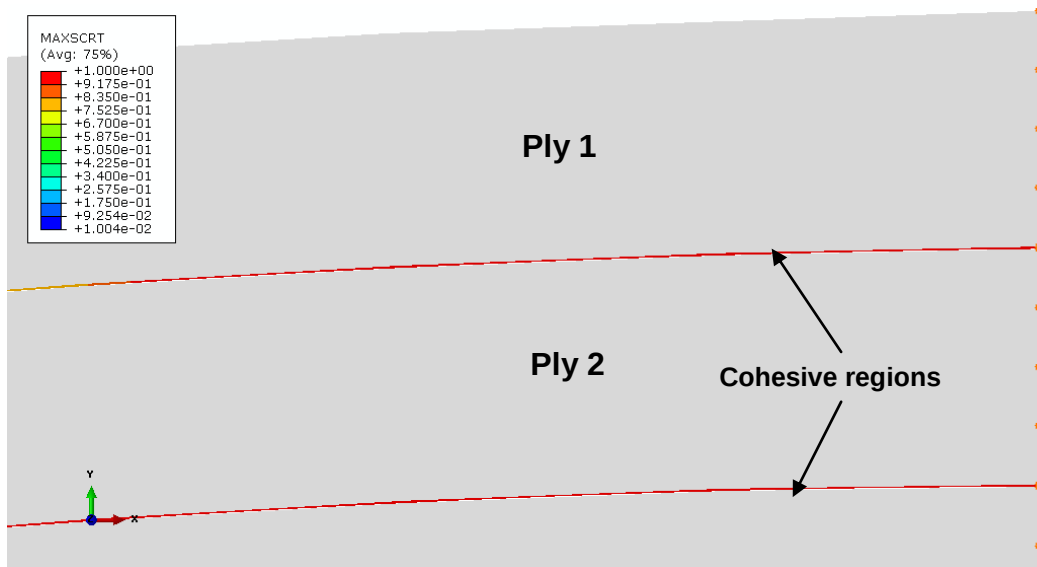


Figure 5. Interface mechanical (MAXSCRT) response (near the clamped zone).

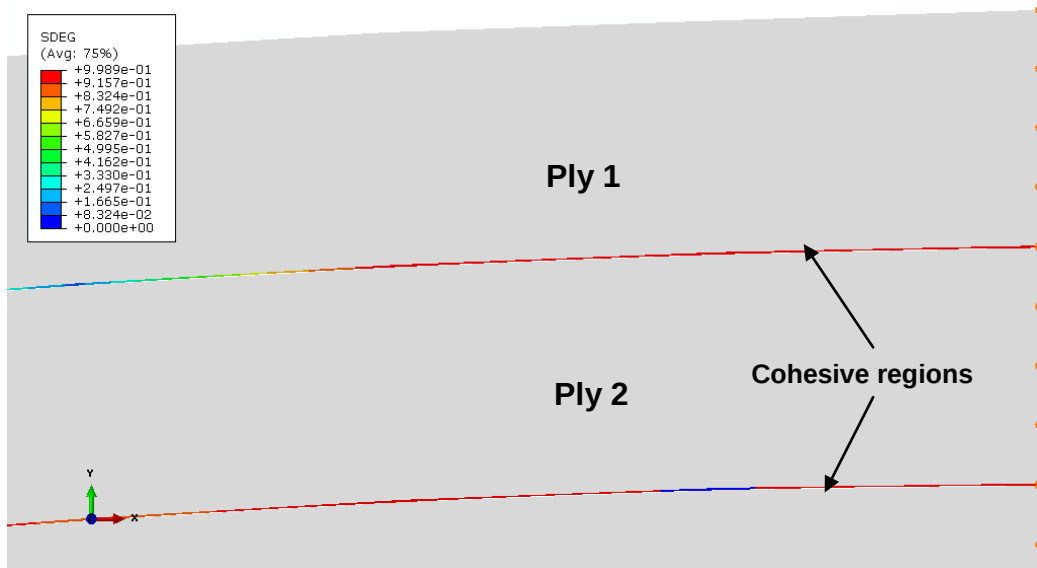


Figure 6. Stiffness degradation scalar field (near the clamped zone).

A mode-base steady-state procedure in the frequency domain of $[0, 60]$ kHz was considered in order to simulate the dynamic response of the structure for the obtained level of damage (and consequent stiffness reduction). Representative structural mode shapes are showed in Figure 7 for the considered frequency range.

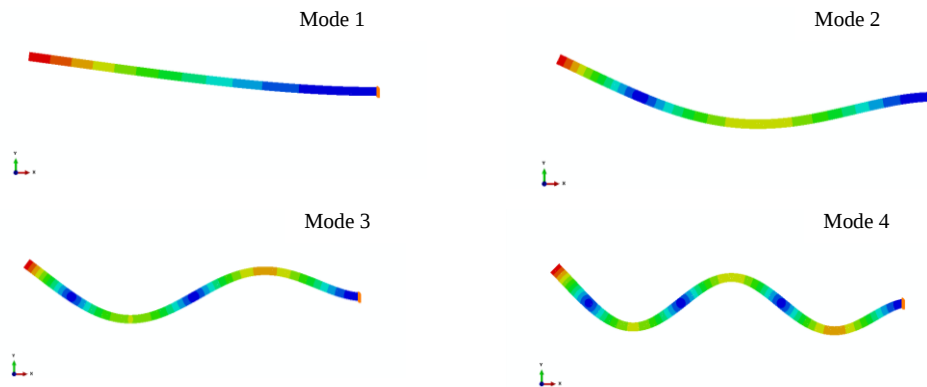


Figure 7. Mode shapes for delaminated structure (2D model).

Normal acceleration values at the beam tip were monitored through the considered frequency range for the two levels of damage previously defined (section 4.1.2). These results are shown in Figure 8.

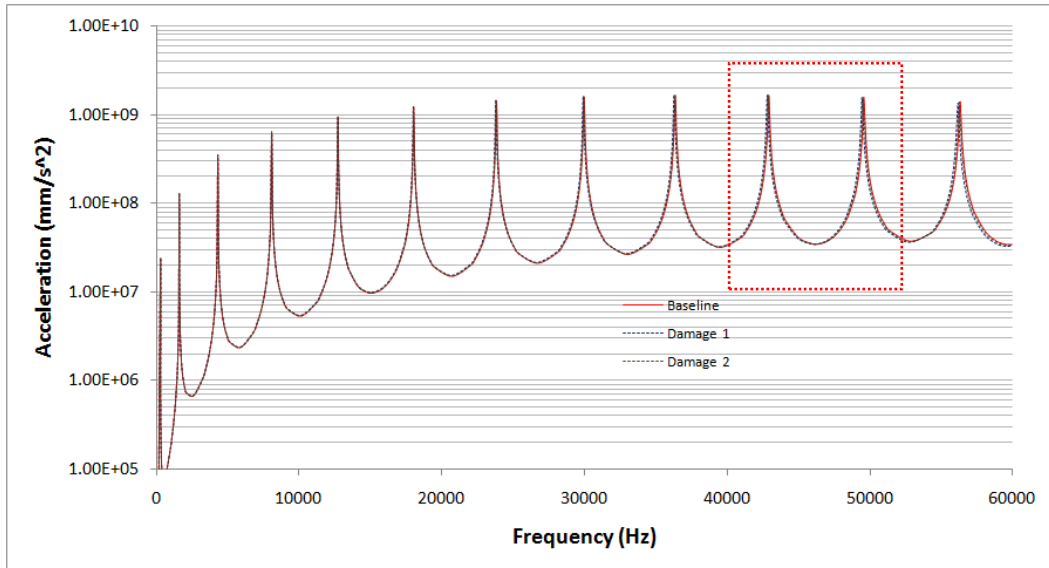


Figure 8. Dynamic response of delaminated structure.

The shift in resonant frequencies, when comparing to a healthy structure with a delaminated one, is visible in Figure 8. The frequency range [40, 53] kHz is plotted in Figure 9 for a better visualization of the results.

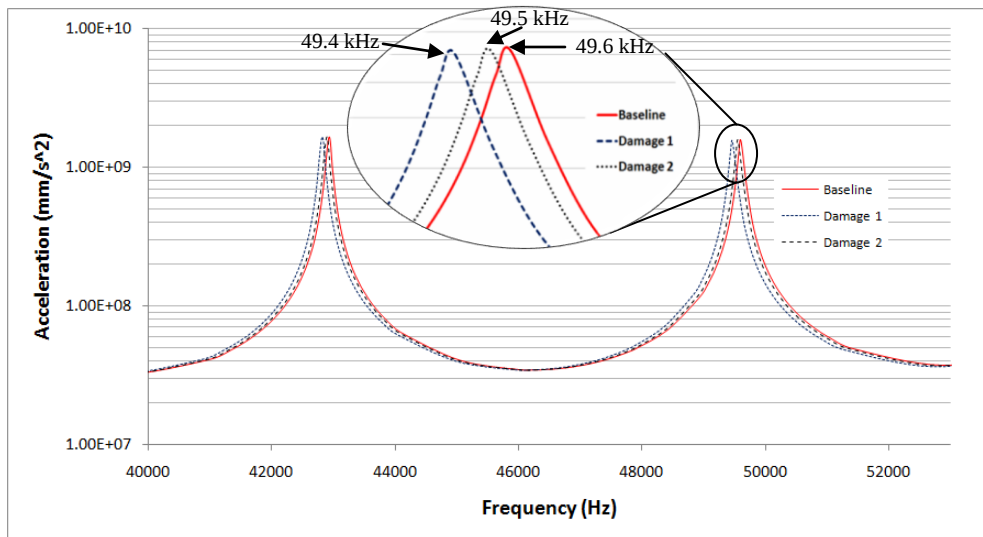


Figure 9. Dynamic response of delaminated structure (enlarged view).

5.2 3D Model

In Figure 10 is plotted the normal displacement field for the three point bending test. Interfacial delamination and consequent interfacial stiffness degradation was achieved for the considered loading conditions in the skin/flange interface as seen in Figures 10 and 11. Correspondent stiffness degradation field for the cohesive region is plotted in Figure 12.

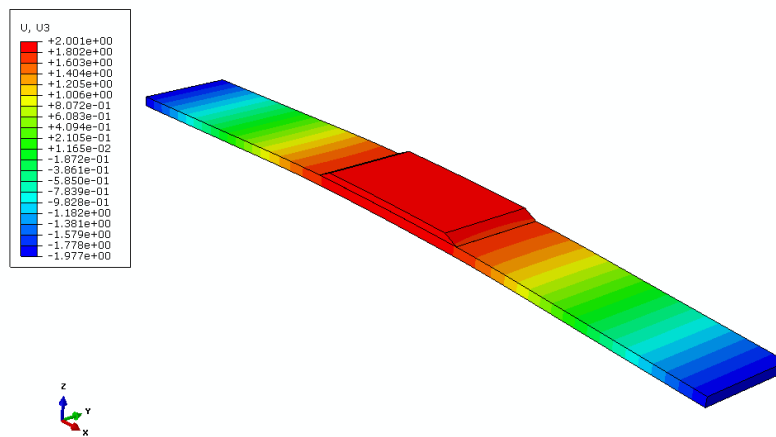


Figure 10. Normal displacement (U3).

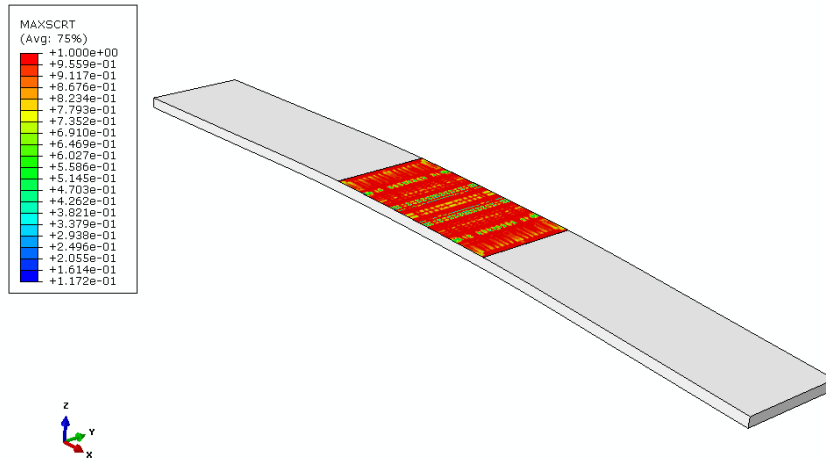


Figure 11. Damage initiation (MAXSCRT) criteria field for the cohesive region.

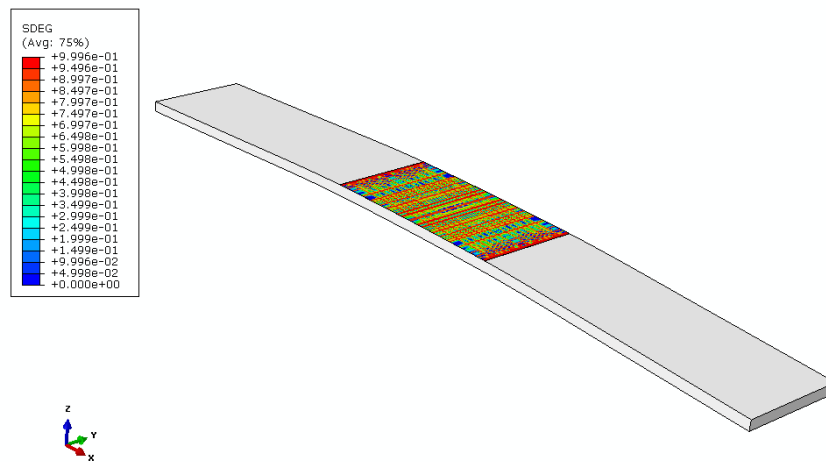


Figure 12. Stiffness degradation scalar (SDEG) field for the cohesive region.

For the dynamic procedure, modes shapes were extracted in the frequency range of [0, 70] kHz. In Figure 13 are depicted some eigenmodes for the healthy structure.

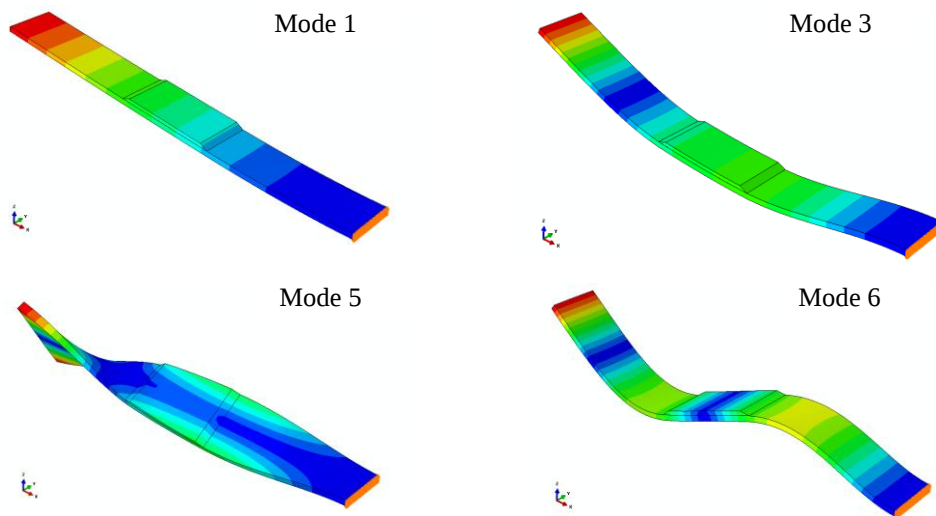


Figure 13. Mode shapes (eigenmodes) for the healthy structure.

The frequency spectrum of the normal component of acceleration monitored at the skin's tip for the healthy (baseline) and delaminated structure is plotted in Figure 14.

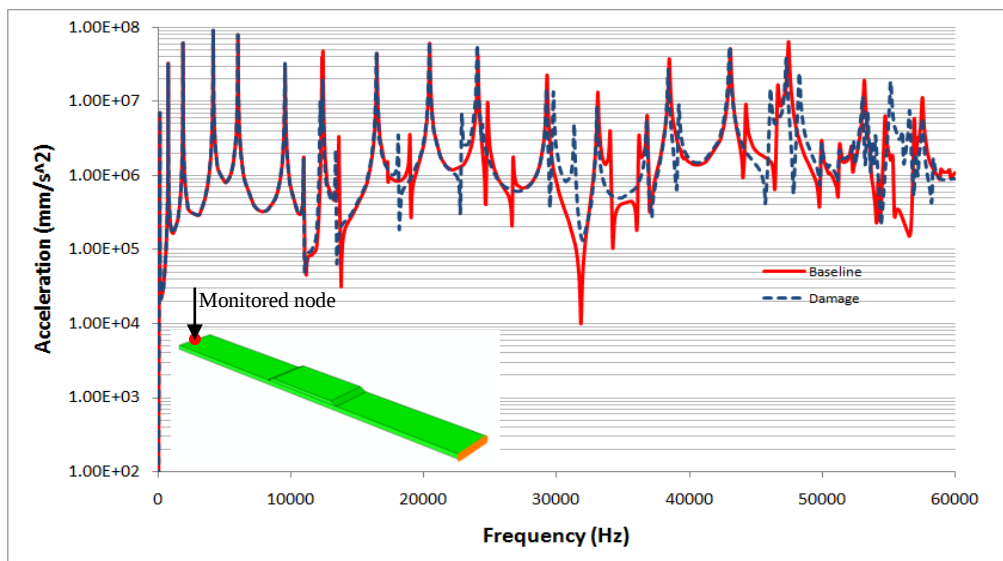


Figure 14. Acceleration spectrum for healthy and delaminated structure.

6. Results discussion

Modal analysis procedures are sensible to the local changes in stiffness introduced by delamination processes for both 2D plane strain and 3D simulation domains considered, as seen in Figures 8/9 and 14, respectively.

The amplitude shift for the resonant frequencies is related with the level of induced damage. In fact, and as visible in Figure 9 for the 2D plane strain case, higher levels of delamination (damage) induce larger amplitude shifts from the baseline state due to more pronounced stiffness decay. In this particular case, the level of delamination for “*Damage 1*” case is higher than the obtained for the “*Damage 2*” case.

Also, and as visible in Figure 9, the resonance peaks for the delaminated structure are shifted for lower values of frequency due to a decrease in the local structural stiffness in result of the delamination processes. Considering the classical structural dynamics theory, the natural frequencies ω_n of a structure are calculated from the ratio of stiffness and mass through Equation 3. As structural stiffness is reduced through delamination, the natural frequencies are shifted for lower values.

$$\omega_n = \sqrt{\frac{K}{m}} \quad (3)$$

In Equation 3, K is the structural stiffness and m the mass.

For both cases (2D and 3D), the change of dynamic response, nominally the shift in resonance peaks, is visible for lower frequencies, but become more pronounced at higher frequencies.

7. Signal processing

Dynamic signals obtained for dynamic implicit procedure are, normally, obtained in the time domain. This dynamic data is normally transformed for the frequency domain for a better understanding of the dynamic response of the structure.

Critical Materials developed internally a signal processing tool that, within Abaqus CAE platform, enables post-processing operations of dynamic signals.

7.1 SPA – Signal Processing in Abaqus rationale

Dynamic finite element analysis in time or frequency-domain demands intensive results post-processing operations (FFT – Fast Fourier Transform, IFFT-Inverse Fourier Transform, Correlation, PSD-Power Spectra Density, CSD-Cross Power Spectra Density, Convolution, Transfer functions, etc...). These operations are normally very time consuming due to the need of exporting results to third-party software’s (Matlab, Scilab, Mathematica, ...) used to execute signal processing operations.

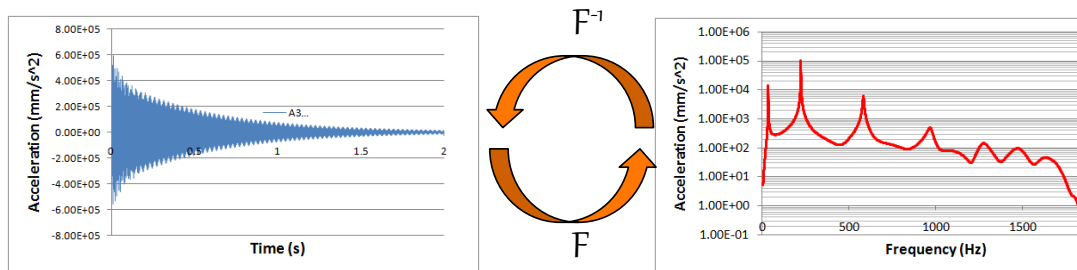


Figure 15 – Time-frequency domain transformations (direct and inverse approach).

SPA-Signal Processing in Abaqus is a signal processing tool developed as a plug-in for Abaqus, using Abaqus GUI Toolkit and Python capabilities. It enables the execution of signal processing operations completely embedded in Abaqus/CAE platform. **SPA** explores the correspondence “one element/node - one sensor” in the sense that nodal or elemental variables are equivalent to experimental data retrieved from experimental sensors. Figure 16 presents selected snapshots of **SPA**’s graphical interface.

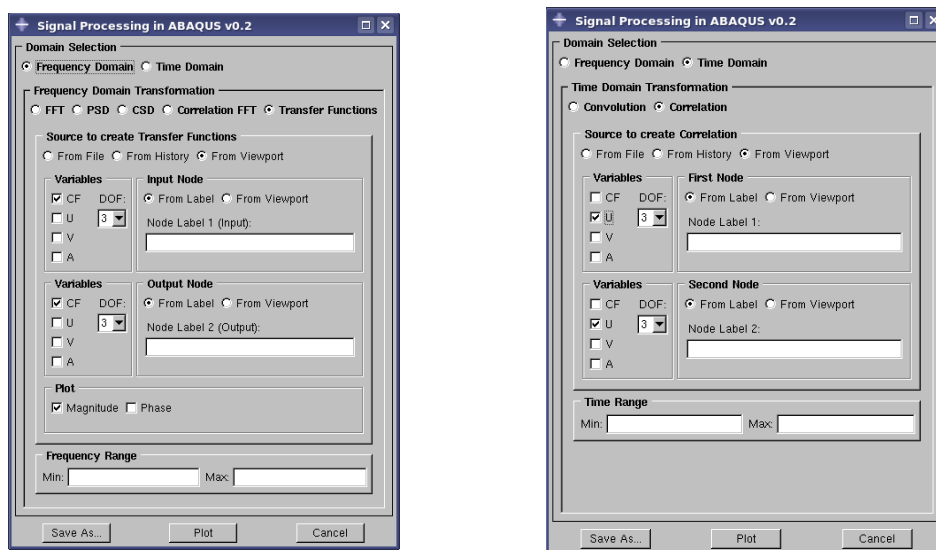


Figure 16 – Snapshots of SPA’s graphical interface.

With **SPA**-Signal Processing in Abaqus, the analyst can interact with the FE model picking nodes (or elements) for which the results are requested, and perform operations in the time or frequency domain.

As an illustrative example, Figure 17 shows the results obtained with SPA application for the computation of a transfer function (magnitude and phase), considering a transient loading of a cantilever bar.

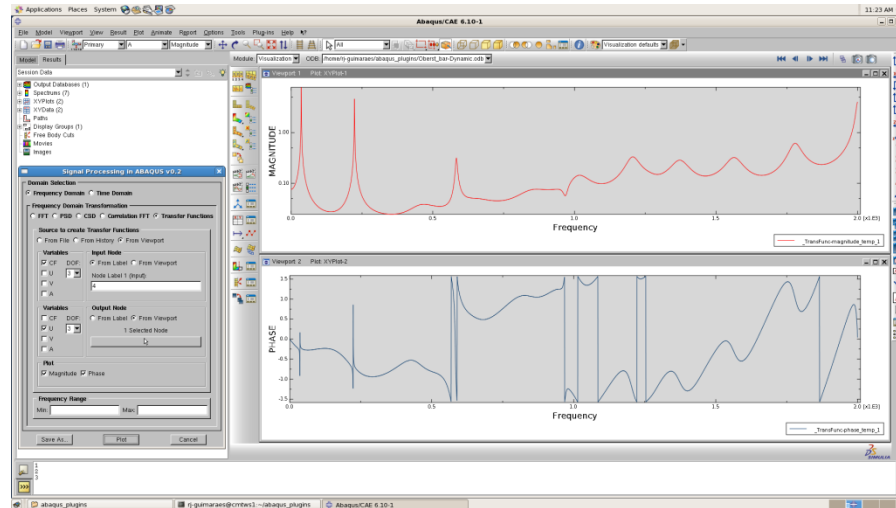


Figure 17 – Results obtained with SPA-Signal Processing in Abaqus.

8. Conclusions

In this article the capability of detecting delamination (damage) in composite structures through changes in the dynamic response of structures was studied. Two finite element models were built to simulate delamination in a 2D plane strain and 3D stress states.

For both cases, modal dynamic analysis procedures could simulate the change in the dynamic behavior of delaminated structures due to changes in local stiffness. The changes in the acceleration spectrum and natural frequencies are visible for the entire considered frequency spectrum but are more pronounced for high frequencies.

The amplitude shift for resonant frequencies can be related with the level of damage, as concluded for the 2D plane strain case. In fact, for higher levels of delamination (damage) more pronounced are the shifts from the baseline's (healthy structure) characteristic resonant frequencies.

SPA-Signal Processing in Abaqus was presented as a signal processing tool, developed as a plug-in for Abaqus, using Abaqus GUI Toolkit and Python capabilities. This plug-in enable embedded signal processing operations in the Abaqus/CAE platform avoiding time consuming externalisation of data processing.

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