

Structural Health Monitoring of Thermoplastic Composite Beams via Vibration-based Method

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Abstract: The present study aims to investigate the capability of new sensors to detect impact-induced damage in composite beams via VBM (Vibration-based Method). Laminated thermoplastic composite beams made of carbon fiber-reinforced polymer (CFRP) made of unidirectional layers are used as specimens in this investigation. Any deviation in vibrational parameters of beams such as mode shapes, natural frequencies, and more importantly frequency response functions (FRFs) by using damage metrics, before and after impact, will be considered as a criterion to identify damage and structural integrity degradation. Besides experimental procedure, numerical simulation of low-velocity impact and vibrational analyses of composite beams will be performed to evaluate the possible advantages/disadvantages of the computational procedure, as well as the potentialities and limitations of the new sensors to be used in SHM (Structural Health Monitoring) systems.

Keywords: *Structural Health Monitoring, Vibration-based method, Damage detection, Damage metrics, FE simulation, Experimental procedure, Composite beam.*

INTRODUCTION

Concerns with the environmental issues and increase in fuel prices have led car and aircraft producing companies to incorporate Fiber-reinforced polymer (FRP) composite materials into their products as desirable substitutions for heavy conventional metallic materials. FRP composites due to their high specific strength and stiffness ratios, besides other suitable mechanical properties such as excellent corrosion and fatigue resistance, have been extensively utilized in the aerospace and automotive industries. Since vehicle (automobile and airplane) structures are likely to experience impact during their lifetime, FRP composites are prone to develop barely visible impact damage (BVID) and visible damages. Thus, a wide range of periodic inspection schemes including the simple visual inspection or advanced X-ray and ultrasonic methods is required to assure structural integrity. In many industries, especially in the aerospace industry, Structural Health Monitoring (SHM) systems have become more desired than the periodic inspection methods since the integrity status of the structure could be monitored continuously (online) and during service. Thus, this continuous monitoring can increase structural safety and reduce expenses.

Several SHM systems like vibration-, optical-, thermal- and impedance-based methods have been used to detect damages (like impact-induced damages)(Loi, Porcu, and Aymerich 2021). Due to simplicity, the vibration-based method has been widely developed by several researchers. Depending on the type of material and damage scenario, the presence of damage can lead to a change in stiffness, damping, mass, or geometry of the structure. This change leads to different dynamic responses from the equivalent intact structure. The vibration-based SHM method assesses the health condition of a specimen by considering dynamic responses(Cuadrado et al. 2022). In this method, vibrational responses of damaged and undamaged specimens, such as mode shapes, natural frequency, Frequency Response Functions (FRFs), and damping behavior, will be compared together.

The present research project aims to investigate the capability of new sensors to detect impact-induced damage in composite beams via VBM (Vibration-based Method). Since the new sensors are still being manufactured, at the present stage this conference paper only presents a similar procedure without using new sensors. Both experimental and numerical methods have been considered herein.

EXPERIMENTAL PROCEDURE

The beam specimen in the present study is a unidirectional laminated composite with $[(0)_{14}]$ stacking sequence. The mechanical properties of CFRP material are listed in Tab. 1.

Table 1 – Mechanical properties of FRP composite.

Properties	Value	Properties	value	Properties	
Elastic properties		Strength parameters		Fracture energies	
E_{11} (GPa)	122.33	X^{T*} (MPa)	1404	G_1^T (N/mm)	90
E_{22} (GPa)	6.78	Y^{T*} (MPa)	21.55	G_1^C (N/mm)	80
G_{12} (GPa)	3.47	S_{12}^* (MPa)	37.71	G_2^T (N/mm)	0.5
Major poison's ratio	0.287	S_{21}^* (MPa)	-	G_2^C (N/mm)	1.5
		X^{C*} (MPa)	800**		
		Y^{C*} (MPa)	200**		

* X (1) represents fiber direction; Y (2) represents the direction transverse to the fibers; T stands for tensile and C stands for compressive properties; S stands for shear strength.

** The values are assumed.

The beam specimen was cut from a unidirectional laminated plate, as illustrated in Fig. 1. The position of the beam on the shaker, impact area, and location of the measuring point are described in Fig. 1.

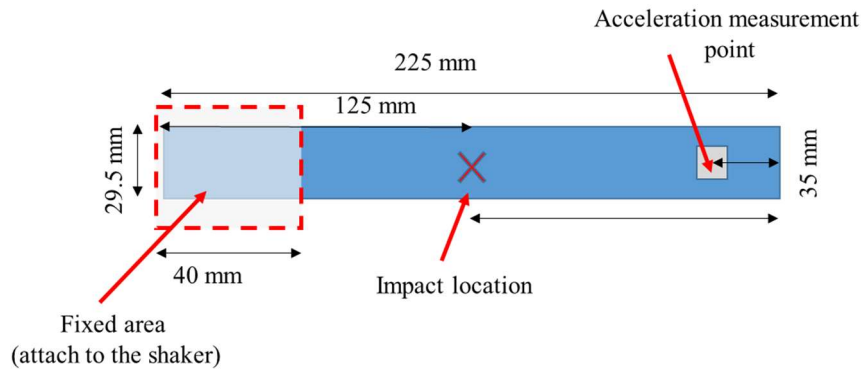


Figure 1- Beam specimens dimension, location of the impact point, cantilever boundary condition, and measurement point.

In the first stage the intact beam was attached to the shaker (cantilever beam) and a harmonic excitation with variable frequency (0 to 550) Hz was applied to the fixation area. A laser vibrometer was utilized to measure the vibrational response of the beam at one point close to the free end of the beam. The vibration test setup is illustrated in Fig. 2. The vibration response (voltage from the laser vibrometer) was acquired 3 times to assure the repeatability of the procedure.

In the second stage, after the vibration test on the undamaged beam, the beam was removed from the shaker and placed under a low-energy drop-hammer facility at the GMSIE laboratory. A fixture designed to hold the beam on the drop hammer anvil during an impact test. The impact setup is presented in Fig. 3. The fixture only covers 60 mm of the beam length to not compressed the sensor that will be attached to the beam. The laser vibrometer (with 900KS/s) was used to record the velocity of the impactor for further calculation. The impactor has a round shape with a 5.4 mm radius and 6.21 kg weight. The impactor was dropped from 203 mm height above the beam.

After performing the impact test on the beam, the damaged beam was placed on the shaker with the same configuration presented in the first stage. The vibration response of the damaged beam at the selected point was recorded to be compared to the vibration response of the intact beam.

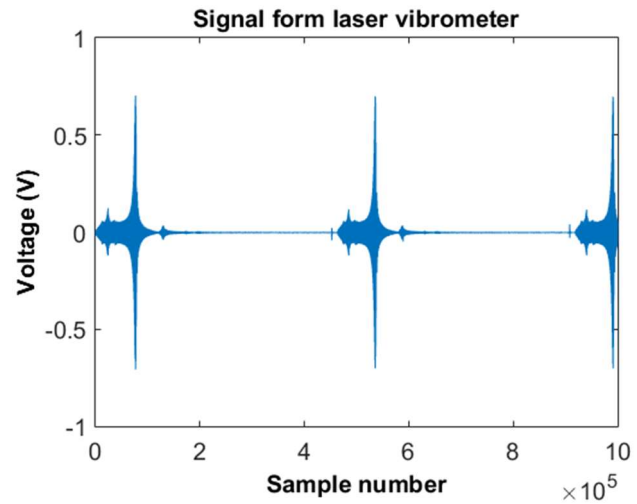
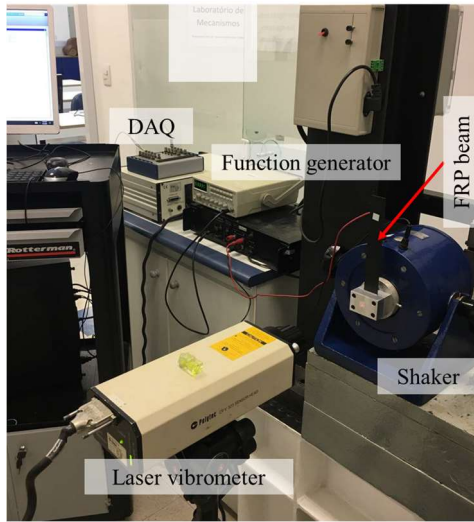


Figure 2- Vibration test setup.

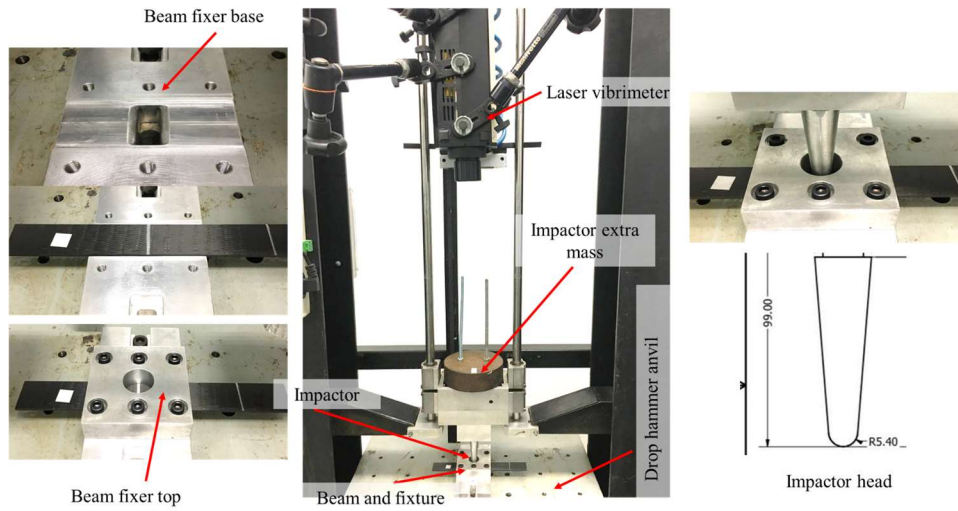


Figure 3 - Low-impact energy test setup.

NUMERICAL PROCEDURE

The numerical simulations of experimental vibration and impact tests explained in the previous section were performed using ABAQUS 6.14. A multi-shell model of the composite beam was developed while the conventional shell element (S4R) was used to discretize the composite layers and interface layers were modeled with the continuum element. The composite shell layers were tied to the neighboring continuum cohesive layer by using the rigid tie. The global element size for all layers is equal to 1×1 mm. The FRP composite beam has $[(0)_{14}]$ layers however, to speed up the simulation this laminated was modeled with three layers of 0-direction laminate and two interface continuum layers $[(0)_5/C1/(0)_4/C2/(0)_5]$. The mechanical properties presented in Table 1 were used as material input parameters. The material model uses Hashin's 2D failure criteria to detect the damage initiation of failure modes (mode I: Fiber tension, mode II: fiber compression, mode III: matrix tension, and mode IV: matrix compression) and an energy-based degradation scheme to soften the material properties after damage initiation point. Figure 5 explains the FE model of the beam by presenting the FE model of impact simulation. The hard contact and tangential behavior with the penalty formula (0.35 friction coefficient) have been considered to act between all layers and surfaces in the FE model. The element-based cohesive model with traction-separation formula was used to represent the interface between composite layers. the mechanical properties of the cohesive layer were adopted from Ref. (Chiu et al. 2016) as listed in Tab. 2.

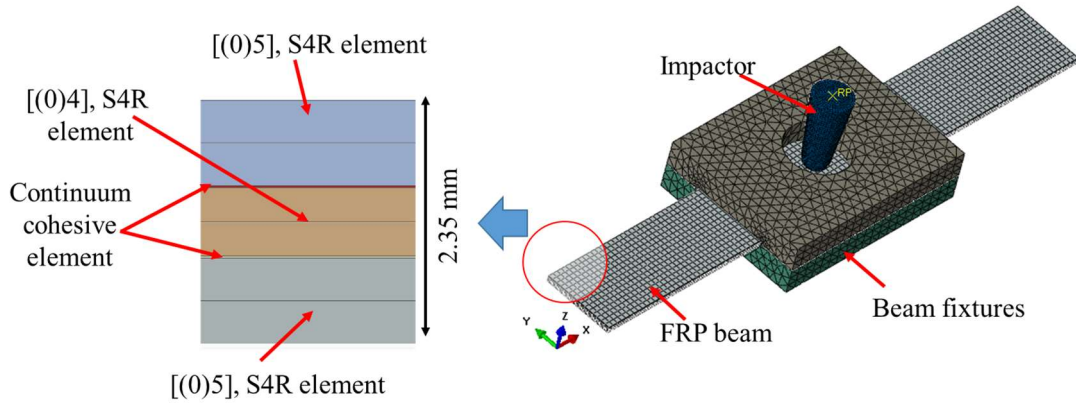


Figure 4 - FE model of impact simulation.

Table 2 – Mechanical properties of the interface layers.

Failure mode	Interlaminar strenthes (MPa)	Interlaminar fracture energies (N/mm)
Mode I	$\sigma_I = 60$	0.331
Mode II	$\sigma_{II} = 60$	0.443

RESULTS

Figure 5 shows the comparison between the vibration response of intact and damaged beams in time and frequency domains.

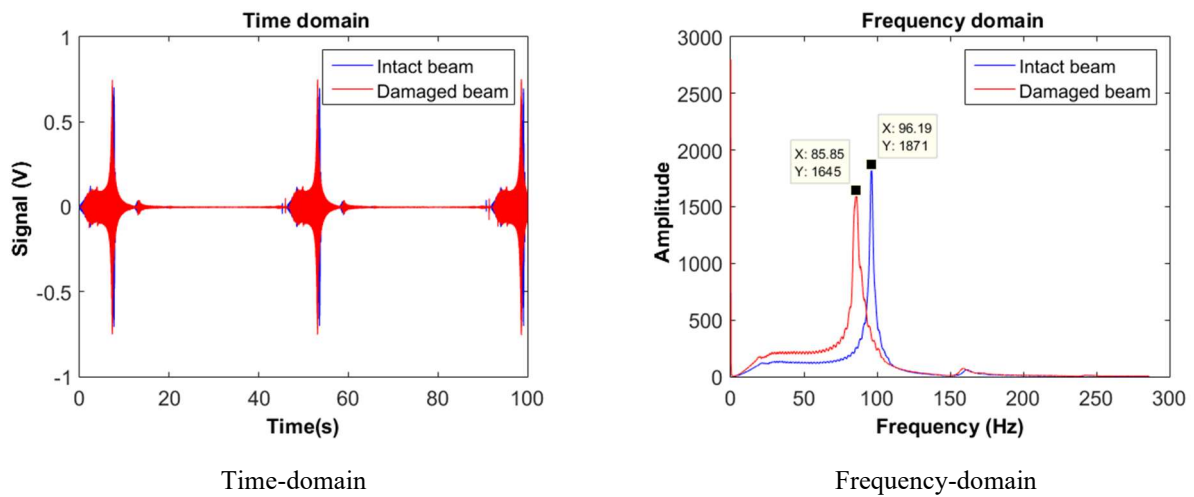


Figure 5 – Effect of damage on the vibration response of composite beam.

Figure 6 illustrates the damage to the beam after the impact test. The lateral impact with 12.3J energy caused remarkable damage including delamination and fiber breakage.

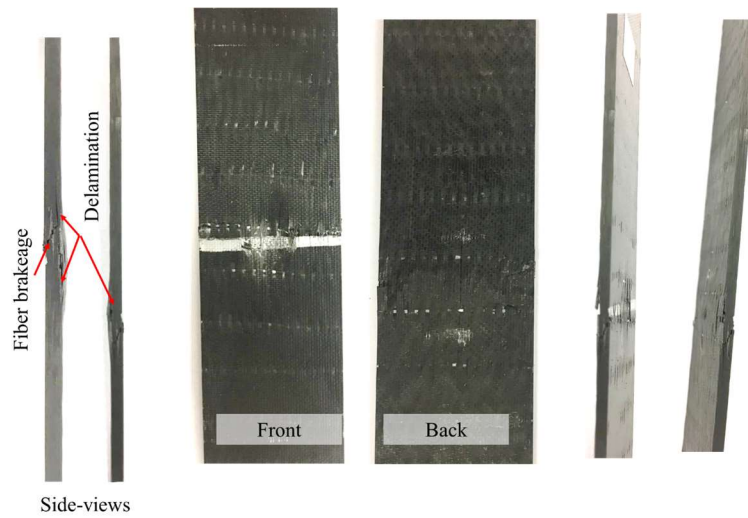


Figure 6 - Damages developed on the beam due to impact test.

Figure 67 compares the impact force history of experimental and numerical simulation. The difference between the force of experimental and numerical simulation is remarkable. The main portion of this difference could be related to the assumption of interlaminar (composite ply) fracture energies and compressive strengths in the fiber and transverse to the fiber direction.

The ABAQUS explicit solver was used to simulate the impact on the composite beam.

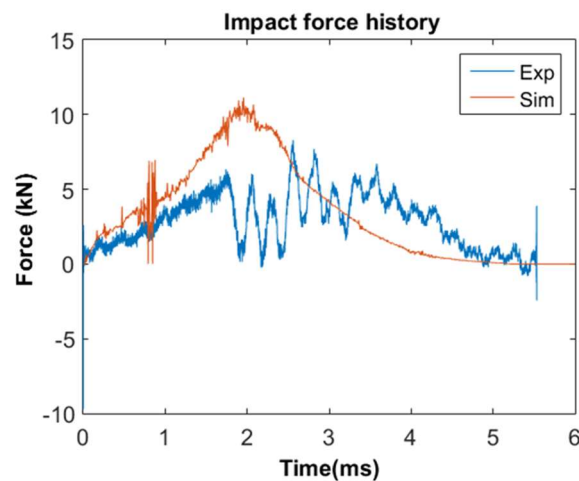


Figure 7- Impact force-time history for experimental test and numerical simulation.

Figure 8 presents the different failure modes of composite plies (only L1, C1, C2) for the end of the step. It is worth noting that the element deletion option for composite plies has been turned off, thus totally failed elements were not deleted from the simulation.



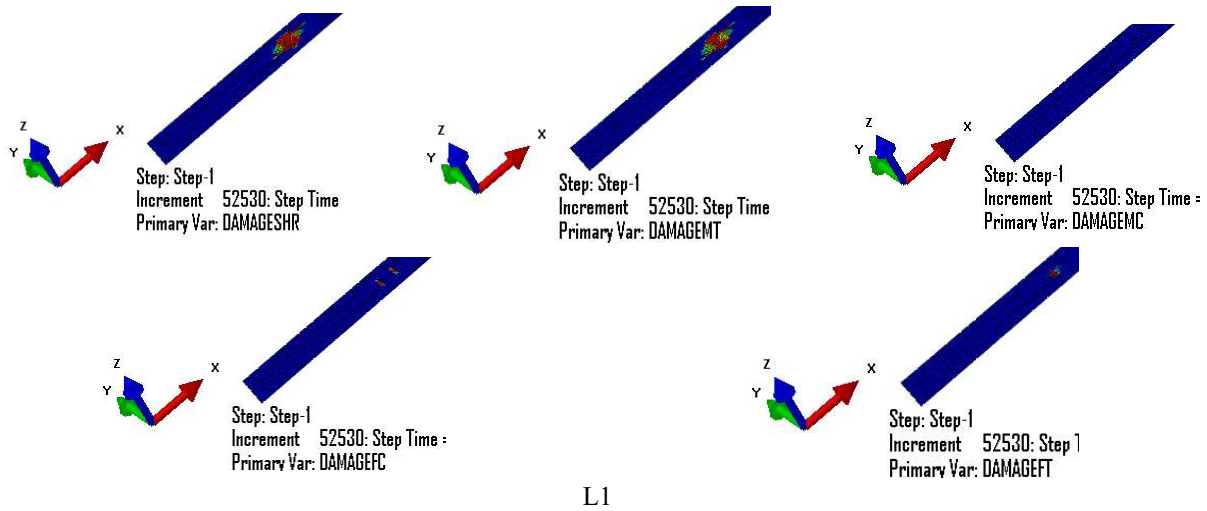


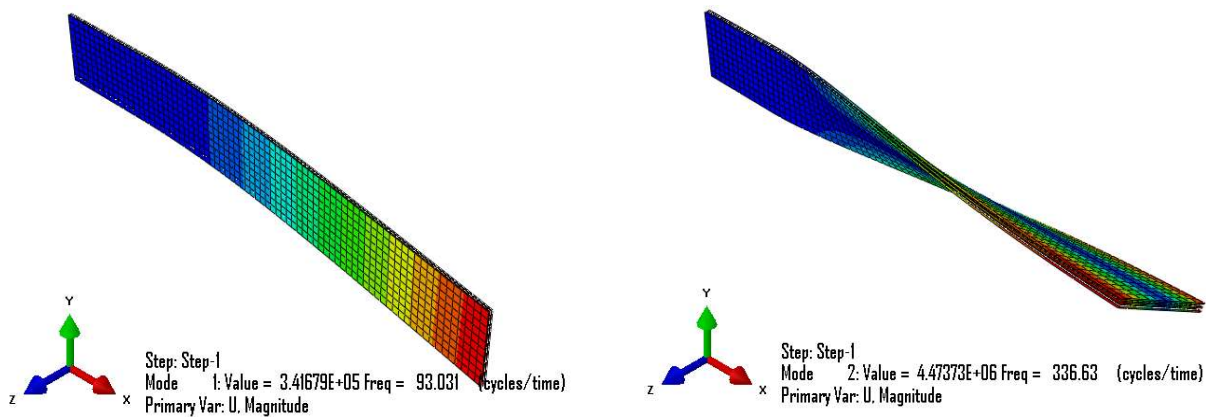
Figure 8 - The damaged layer of the composite beam.

Abaqus/Standard was used to perform vibration simulation similar to the experimental procedure. The damaged model of the beam after impact explicit simulation is transferred to the ABAQUS Standard to compare the vibration behavior of intact and damaged models via FEA.

Modal analysis on the damaged and undamaged cantilever beams (with the same boundary condition of the beam in the experimental vibration test) was performed and natural frequencies and mode shapes are presented in Tab. 3 and Fig. 9 and 10.

Table 3 - Comparison between natural frequencies of intact and damaged beams (numerical simulation).

Beam model	Frequencies (Hz)					
	f_1	f_2	f_3	f_4	f_5	f_6
Intact beam	93.03	336.63	569.54	945.54	1100.01	1539.50
Damaged beam	74.82	281.50	438.84	684.13	915.45	1191.30
	19.57	16.30	23.00	27.64	16.77	22.61
Difference (%) $(1 - \text{damaged/intact}) \times 100$						



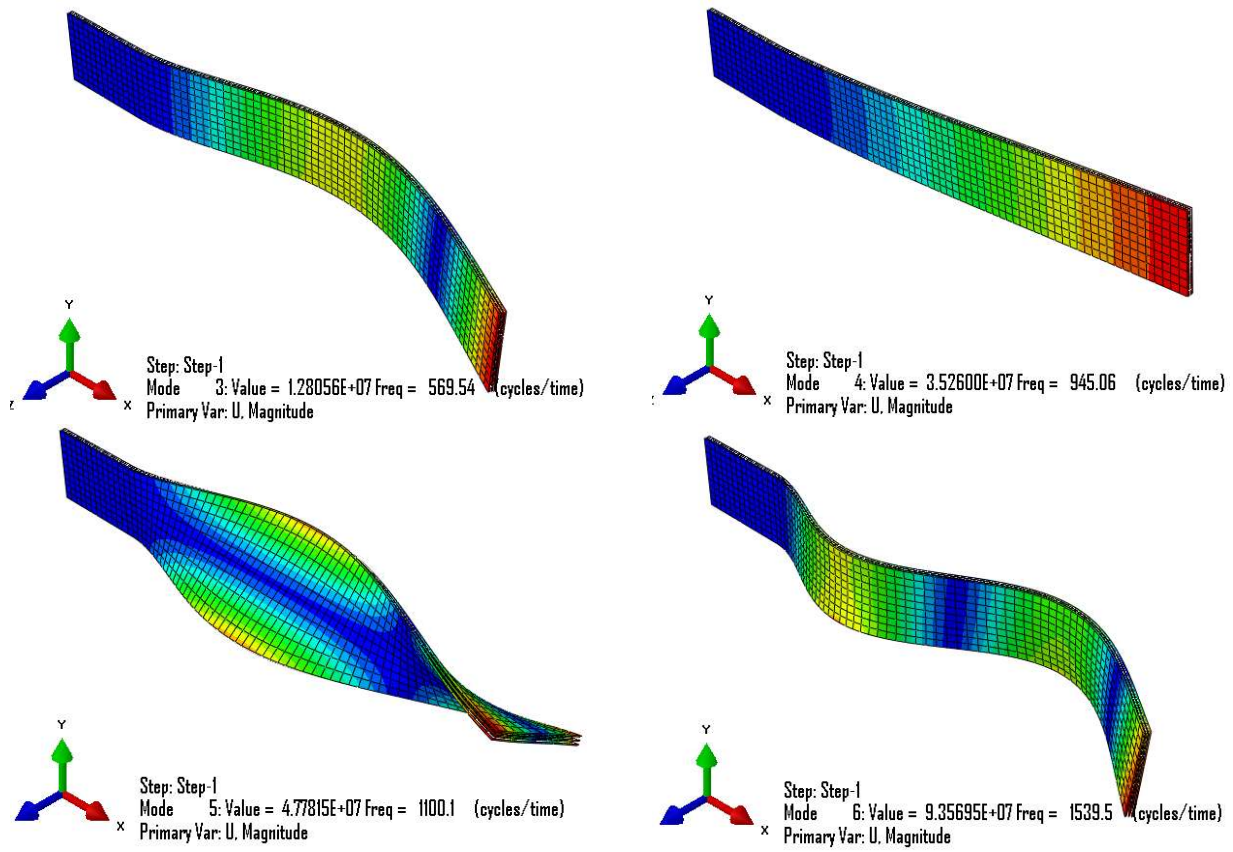
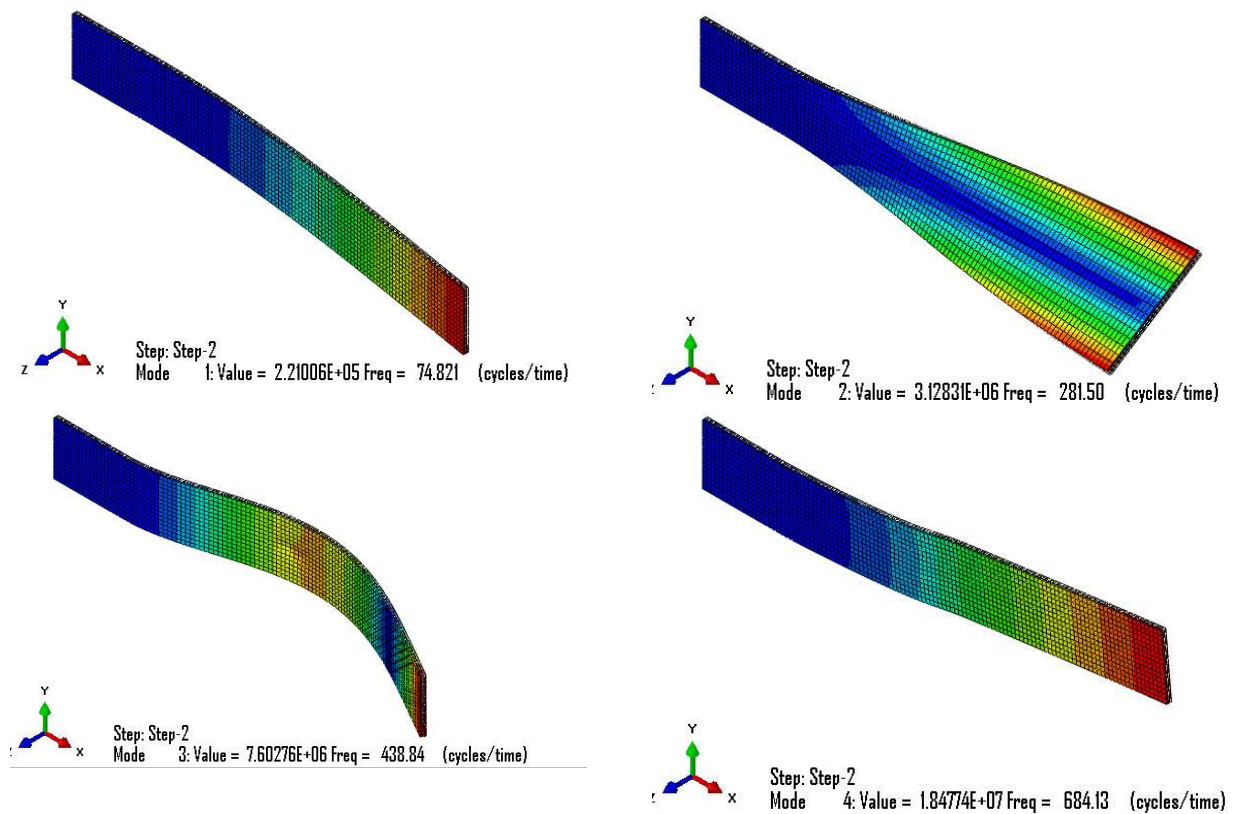


Figure 9 - Mode shapes of the intact beam.



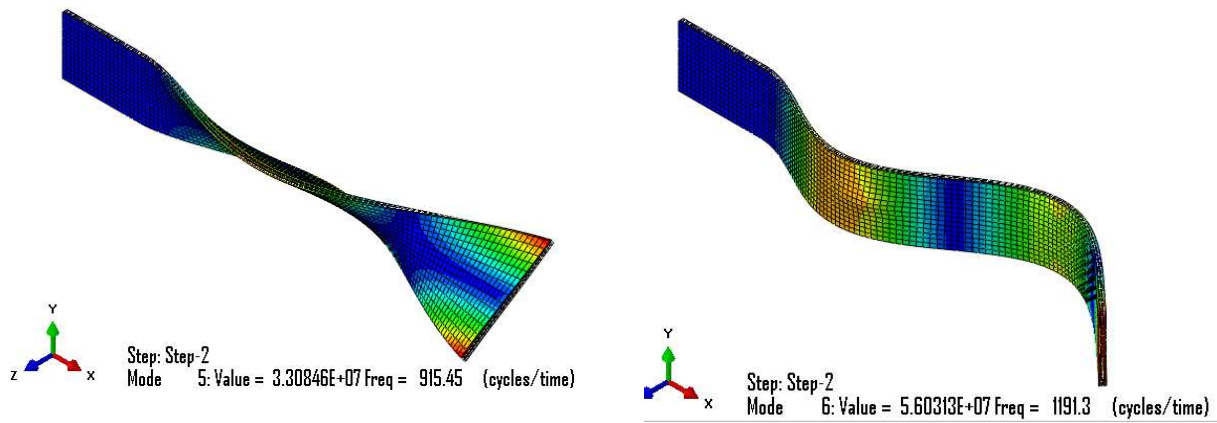


Figure 10 - Mode shapes of the damaged beam.

CONCLUSIONS

This work presents a numerical/experimental framework to detect the impact-induced damage to FRP composite materials through the correlation between the vibration response of intact and damaged beams. This framework will be utilized in the future to assess the damage detection capability of the new sensor that is going to be developed and tested in Portugal and Brazil.

ACKNOWLEDGMENTS

The authors are thankful for the support of Dean's Office of Researcher of the University of Sao Paulo via "PIPAE - PROJETOS INTEGRADOS PARA PESQUISAS EM ÁREAS ESTRATÉGICAS". Volnei Tita would like to thank the National Council for Scientific and Technological Development (Conselho Nacional de Desenvolvimento Científico e Tecnológico; process number: 310656/2018-4).

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