

Sensitivity Analysis and Damage Identification in Composite Plates

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Abstract: The presence of composite materials in primary and secondary aircraft structures has increased over the years, combined with the use of Structural Health Monitoring systems for the monitoring and assessment of the real conditions of the structure. In this work, vibration-based methods and damage metrics are employed to monitor composite plates subjected to a controlled damage. A sensitivity analysis is also carried out to determine how much uncertainties in the mechanical properties of the structure can affect its modal response and the results are used to create an envelope for the expected frequency response of the plate. An experimental modal analysis was conducted in the plate in its intact condition and later three levels of damage were introduced in the plate and new modal analyses were carried out. The results were used to evaluate the performance of three different damage metrics.

Keywords: Structural Health Monitoring, Sensitivity Analysis, Finite Element Analysis, Controlled Damage

INTRODUCTION

The presence of composite materials in primary and secondary aircraft structures has increased over the years. However, the lack of a complete understanding of the mechanical behavior of such structures prevents an optimum design by imposing high safety factors. One way to work around this problem and still guarantee the reliability of the structure is by using Structural Health Monitoring (SHM) systems. In a SHM system, the structure can be continuously monitored, and its “health” state evaluated, so that damages may be detected in an early stage, long before they lead to catastrophic failures.

Thus, a SHM system strongly depends on non-destructive techniques that have the ability to evaluate and determine the presence of damage in a structure in service. For this purpose, a widely used technique is a method based on the vibrational response of the structure, usually via the analysis of the structure’s Frequency Response Function (FRF). However, even two identical undamaged structures can show small differences in terms of FRFs, because structural dynamics behavior exhibit scatter. Thus, it is necessary to calculate damage metrics in order to better identify damage in the structure (Sartorato et al, 2017). Additionally, uncertainties in the mechanical properties of a structure may further increase the difficulties in damage identification, especially for techniques that rely on numerical modeling of the structure.

Therefore, in this work, an investigation will be conducted on a composite plate to first verify its sensitivity to uncertainties in the mechanical properties, and later to evaluate the efficiency of some damage metrics in damage detection. The methodology for the sensitivity analysis is based on the work of Souza, Tita, and Medeiros (2017), while for damage identification will be investigated the damage indexes proposed by Monaco, Franco and Lecce (2000), Mickens et al. (2003) and Sartorato et al. (2017).

MATERIALS

The structure analyzed in this work is a plate made of carbon fiber reinforced polymer (CFRP). The laminate is made of carbon fibers in a polymeric matrix of polyphenylene sulfide (PPS). The stack configuration is $[0^{\circ}/90^{\circ}]_7$. The plate has dimensions of 390 mm x 365 mm and an average thickness of 2.19 mm. As the plate did not possess a perfectly flat surface, a 3D coordinate measuring machine was used to map the position of 400 points distributed on each side of the plate. Based on the 3D surface, it was created a geometry in CAD to be used in the modal Finite Element Analysis (FEA). The plate was initially in a pristine condition, but for later analysis, damage was introduced in the plate via the insertion of two cuts with 2.3 mm thick on the border of the plate, and three levels of damage were evaluated (namely with cutting sizes L_c equal to 30 mm, 60 mm and 90 mm). The plate and damage geometry are shown in Fig. 1 below.

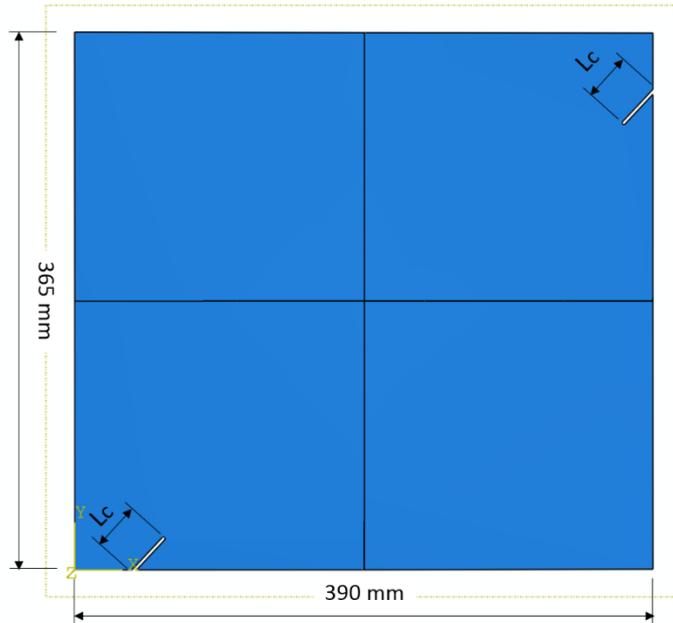


Figure 1 – Plate and damage geometry used in this work.

NUMERICAL SIMULATIONS AND SENSITIVITY ANALYSIS

The numerical simulation via FEA was performed in ABAQUS™ v6.14. The plate was modeled by four node shell elements with reduced integration (S4R). Free-free boundary condition was used in the model to obtain the vibrational modes of the plate.

In order to verify the sensitivity of the plate to the mechanical properties used in the modal simulation, a sensitivity analysis was performed based on the Taguchi experimental design L8 matrix, and the following parameters were analyzed: E_1 , E_2 , G_{13} , G_{12} , G_{23} , ν_{12} , ρ (where direction 1 is aligned to the fibers, 2 is normal to the fibers, and 3 is normal to ply plane). It was assumed a variation of $\pm 10\%$ in the nominal mechanical properties of the material and a $\pm 5\%$ variation in the density to generate both levels of the Taguchi matrix. The nominal values for the mechanical properties were obtained in Angélico (2013), who studied the same material. Table 1 contains the two levels of the values used in this analysis:

Table 1 – Level 1 and 2 of the parameters used in the sensitivity analysis.

Factor	Level 1	Level 2	Unit
E_1 (Young's modulus)	47.43	57.97	GPa
E_2 (Young's modulus)	46.35	56.65	GPa
ν_{12} (Poisson's ratio)	0.054	0.066	-
G_{12} (Shear modulus)	3.6	4.4	GPa
G_{13} (Shear modulus)	3.6	4.4	GPa
G_{23} (Shear modulus)	3.6	4.4	GPa
ρ (density)	1480.0	1635.8	kg/m ³

Based on the values of Tab. 1, an L8 matrix was built to define each combination of properties to be used in the numerical sensitivity analysis. These combinations are shown in Table 2.

Table 2 – Taguchi's L8 matrix with the combinations used in each simulation (run).

	E_1	E_2	G_{13}	G_{23}	G_{12}	ν_{12}	ρ
Run 1	47.43	46.35	3.6	3.6	3.6	0.054	1480.0
Run 2	47.43	46.35	3.6	4.4	4.4	0.066	1635.8
Run 3	47.43	56.65	4.4	3.6	3.6	0.066	1635.8
Run 4	47.43	56.65	4.4	4.4	4.4	0.054	1480.0
Run 5	57.97	46.35	4.4	3.6	4.4	0.054	1635.8
Run 6	57.97	46.35	4.4	4.4	3.6	0.066	1480.0
Run 7	57.97	56.65	3.6	3.6	4.4	0.066	1480.0
Run 8	57.97	56.65	3.6	4.4	3.6	0.054	1635.8

From each simulation (Run), the values of the first eight natural frequencies of the plate were analyzed. Based on these results, it was possible to calculate the impact factor I , defined by Eq. (1), of each parameter, in order to quantify which of them has the biggest influence on the modal analysis of the intact plate.

$$I = \sum_{k=1}^8 \frac{\text{abs}(M_1^k - M_2^k)}{V} \quad (1)$$

where the value I of a certain parameter is calculated via M_1^k and M_2^k , which are the mean value of the natural frequency from mode k influenced by level 1 and level 2 respectively, and V is the percentage variation of the parameter.

Table 3 below presents the results for the parameters evaluated:

Table 3 – Impact factor and rank position of each parameter.

Factor	I	Rank
E_1	44.254	2
E_2	18.877	3
ν_{12}	1.846	5
G_{12}	11.884	4
G_{13}	1.309	6
G_{23}	0.510	7
ρ	71.703	1

The sensitivity analysis conducted based on the Taguchi matrix showed that density was the parameter with the highest influence on the modal response of the plate. However, density is usually an easily controlled parameter in the manufacturing process, therefore, the analysis will be restricted only to the influence of the elastic properties. It was found that the influence of the elastic properties is in the following order (from highest to the lowest influence): E_1 , E_2 , G_{12} , ν_{12} , G_{13} , G_{23} . By selecting the first four properties, which provide a higher influence on the modal analysis, a full factorial matrix was built, generating 16 combinations among the parameters chosen.

From the 16 simulations, an envelope was constructed with the minimum and maximum values expected for the FRF of four different points of the plate (as measured by the accelerometer 1). The points were chosen as shown in Fig. 2, which also shows the experimental set-up for the modal identification test.

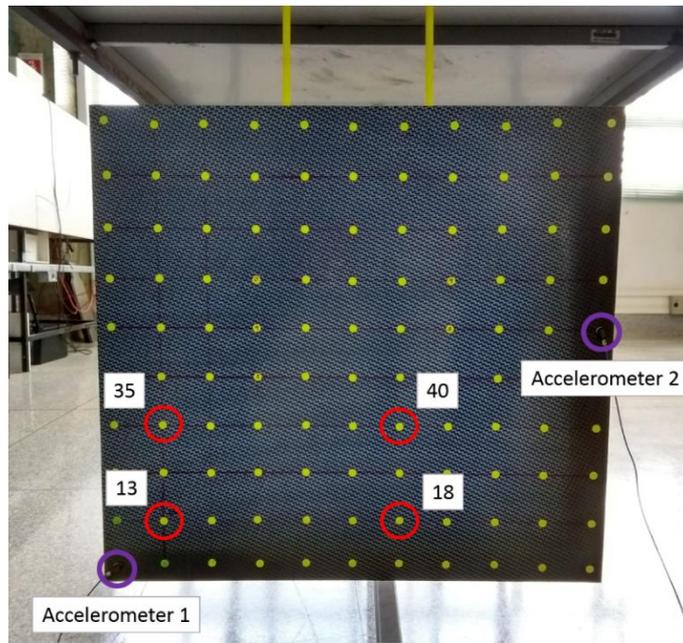


Figure 2 - Set-up of the experimental modal identification test highlighting the position of the four points, which were used in the sensitivity analysis.

For the experimental modal analysis of the structure, an impact hammer was used to excite the plate with an impulse force while two accelerometers recorded the plate’s response. A grid of 110 points was created, and the points were numbered from 1 to 110 starting in the lower left to the upper right corner. The points will be henceforth identified as HXX, where XX stands for the number of the point. The impact hammer would rover through the points while the accelerometers were kept in a fixed position (Accelerometer 1 is in point H1 and Accelerometer 2 is in point H66). Both the accelerometers and hammer were linked to an LMS SCADAS Mobile equipment, which was controlled by the Test.Lab software (LMS Test.Lab™). The modal identification was restricted to a frequency range from 0 to 512 Hz and 2048 spectral lines were used. The plate was hanged by two elastomeric wires to simulate a free-free boundary condition. After the completion of the vibrational impact test, the data post-processing was carried out by PolyMAX, which is a frequency domain parameter estimation method embedded in Test.Lab software.

RESULTS

Sensitivity Analysis

The modal identification was focused in the first six vibrational modes of the CFRP plate. Table 4 presents a comparison between the first six natural frequencies of the intact plate (without damage) obtained via the numerical simulation and the ones obtained experimentally using the results from the modal impact test and:

Table 4 – Comparison between experimental and numerical natural frequencies.

Numerical Natural Frequency [Hz]	Experimental Natural Frequency [Hz]	Error
		$\frac{ NNF-ENF }{NNF}$
27.39	29.16	6.46 %
86.05	86.44	0.45 %
99.10	95.91	3.22 %
102.43	101.89	0.53 %
111.48	104.88	5.92 %
171.34	163.33	4.67 %

Using the procedure detailed above for the sensitivity analysis, a set of 16 FRFs were obtained via FEA for each one of the previously selected points shown in Figure 2, and an envelope was constructed with the minimum and maximum values found for each frequency. It is important to highlight that the critical damping factors obtained from the

experimental modal analysis were used in the simulation. In Fig. 3 it is shown all the 16 FRFs obtained for point H40, whose limits were then used to construct the envelope that was expected to contain the experimental FRF. Figures 4 and 5 show the envelope obtained and compares it with the experimental FRF found for each of the four selected points.

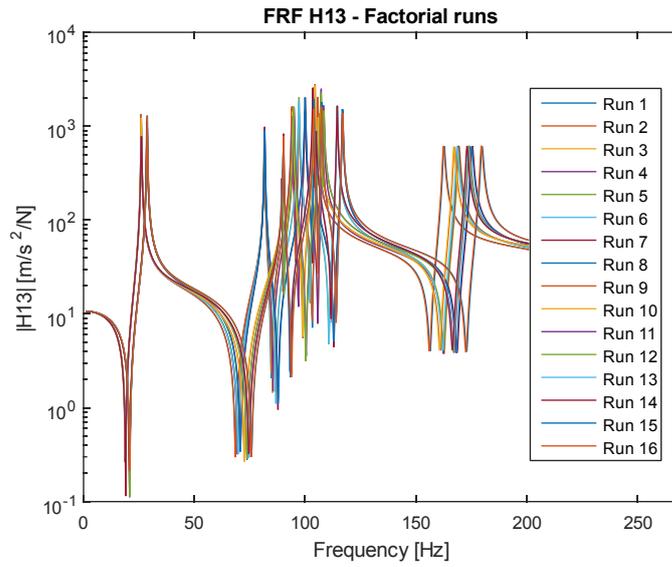


Figure 3 – The 16 FRFs obtained via FEA for the sensitivity analysis of point H40.

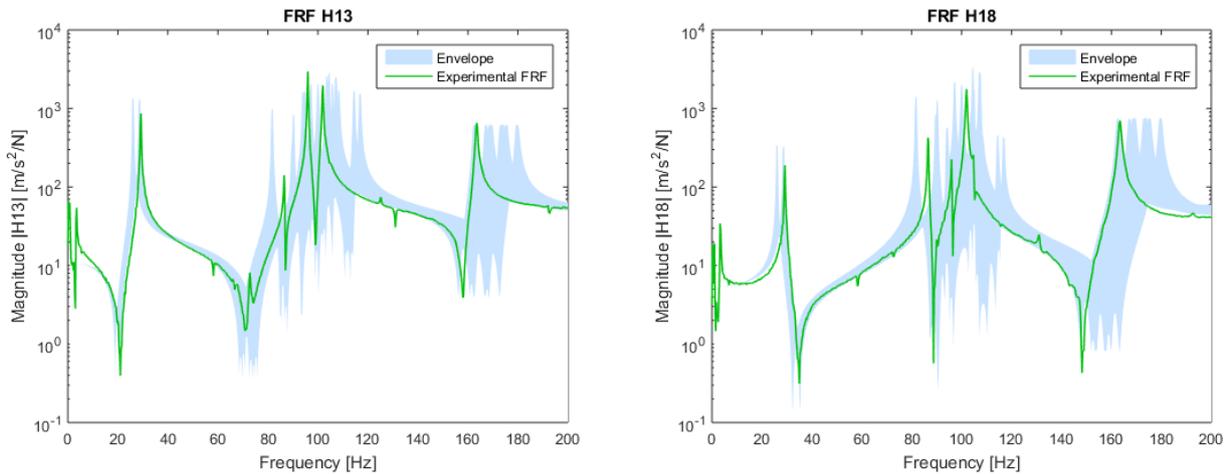


Figure 4 – Experimental values vs. FEA envelope (upper and lower limits) for FRFs of H13 and H18.

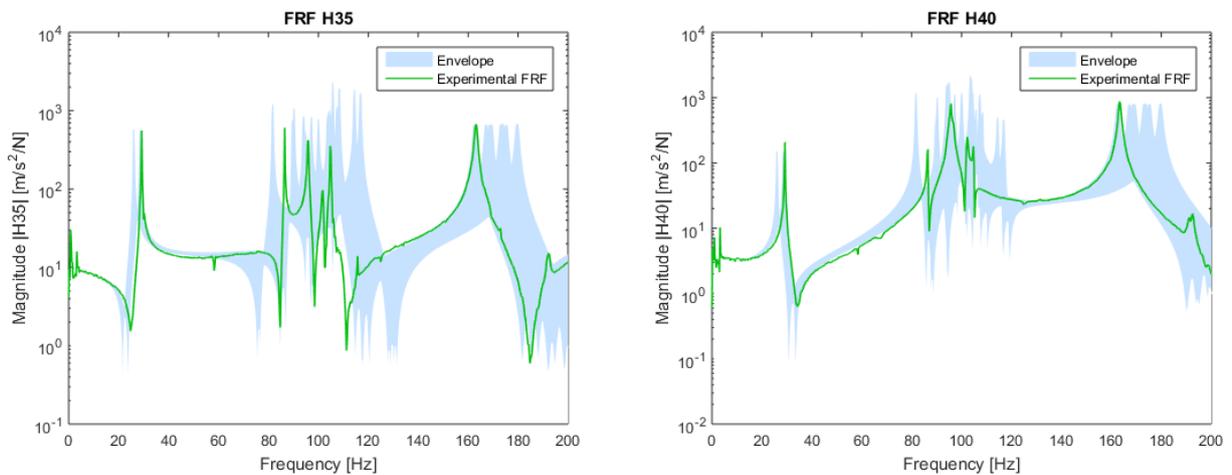


Figure 5 – Experimental values vs. FEA envelope (upper and lower limits) for FRFs of H35 and H40.

Damage Identification

There are several techniques that can be used for damage identification from vibrational tests. The simplest one is the direct comparison of natural frequencies from the damaged structure with its natural frequencies from the pristine condition. Although easy to implement, this method has typically low sensitivity because shifts in natural frequency are usually associated with high levels of damage. In this sense, it is convenient to use damage metrics to help quantify the damage level. Damage metrics can be more effective because they operate in all frequency range of interest, and not only in the resonant region of the FRF.

Table 5 below shows the experimental results for the natural frequency of the first six vibrational modes of the structure in its pristine (intact) state, and with the damage scenarios $L_c = 30 \text{ mm}$ (Damage Level 1); $L_c = 60 \text{ mm}$ (Damage Level 2); and $L_c = 90 \text{ mm}$ (Damage Level 3).

Table 5 – Experimental natural frequencies of the first six vibrational modes of the structure with different damage levels.

	Pristine	Damage Level 1	Damage Level 2	Damage Level 3
Mode 1	27.39 Hz	28.96 Hz	28.00 Hz	26.83 Hz
Mode 2	86.05 Hz	86.58 Hz	86.14 Hz	80.15 Hz
Mode 3	99.10 Hz	95.94 Hz	94.52 Hz	86.48 Hz
Mode 4	102.43 Hz	102.70 Hz	102.28 Hz	97.04 Hz
Mode 5	111.48 Hz	104.86 Hz	103.25 Hz	100.026 Hz
Mode 6	171.34 Hz	164.65 Hz	163.20 Hz	160.63 Hz

As it can be seen from the results above, the natural frequencies present very small shifts for the first two damage levels, although the discrepancies increase as one goes to higher modes. For the very severe damage scenario of Damage Level 3, it can be observed that even the lower modes display a high shift in frequency when compared to the pristine state. In general, it is expected that the presence of damage in a structure is reflected as a reduction in its natural frequencies. However, the natural frequencies for the first two modes in Damage Levels 1 and 2 show a slight increase when compared to the pristine condition. This may be due to noise during the experimental analysis. As explained in Monaco, Franco and Lecce (2000), experimentally it is impossible to accurately measure two FRFs exactly the same way because of the effect of environmental and electrical noise.

The need for damage metrics to quantify damage in a structure is made clear in Fig. 6 below, which shows the FRF H38 of the plate in its intact condition and compares it to the first two damage levels. As it can be seen, the difference between the curves is very small, even for a relatively severe damage on the border of the plate (as is the case for Damage Level 2).

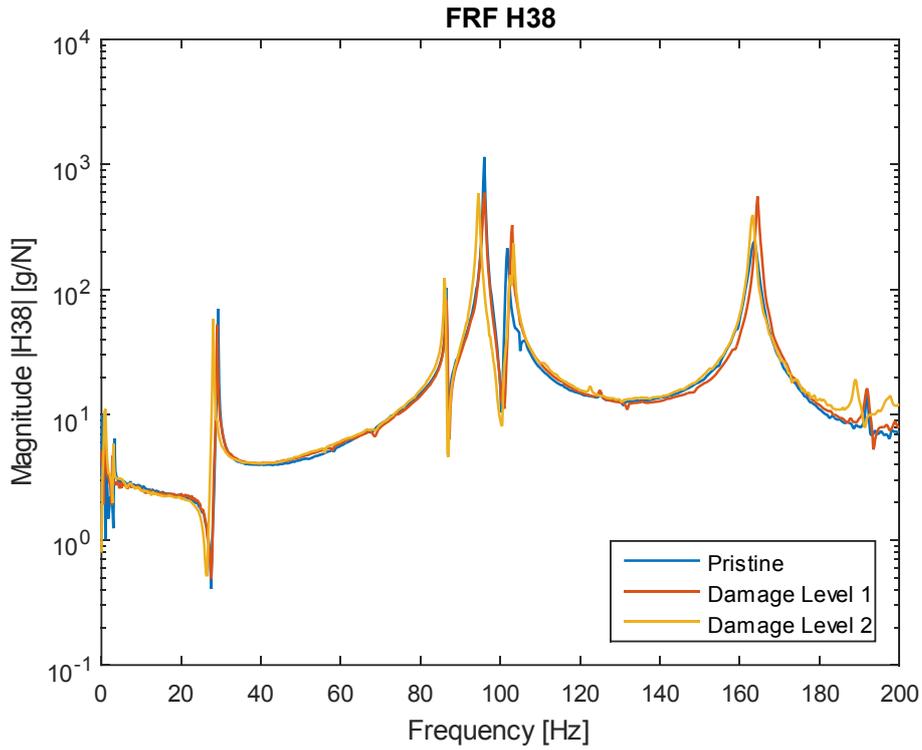


Figure 6 – Experimental FRFs of point 38 for the intact and damaged (Levels 1 and 2) conditions.

In Fig. 7 below it is shown the FRFs of point H40 for the intact condition and for all the three damage levels. It can be observed that large differences in the FRF appear only for the highest damage level studied (that is, Damage Level 3).

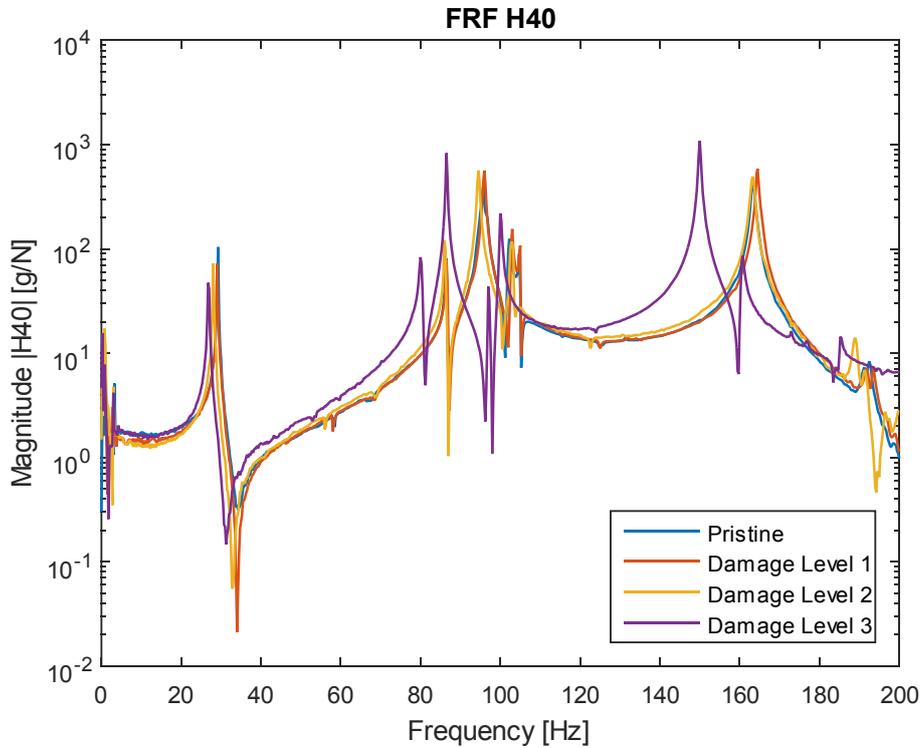


Figure 7 - Experimental FRFs of point 40 for the intact and damaged (Levels 1 and 2) conditions.

In this work, three damage metrics based on the FRF of the structure will be investigated. The first metric (Metric I), shown in Eq. (2), was proposed by Monaco, Franco and Lecce (2000). The second one (Metric II), shown in Eq. (3), was proposed by Mickens et al. (2003); and Metric III, shown in Eq. (4), was proposed by Sartorato et al. (2017).

$$\text{Metric I} = \frac{\sum_{i=1}^N |H_I(f_i) - H_D(f_i)|}{\sum_{i=1}^N |H_I(f_i)|} \quad (2)$$

$$\text{Metric II} = \frac{\Delta f}{f_c - f_0} \sum_{i=1}^N \left| \frac{H_D(f_i) - H_I(f_i)}{H_I(f_i)} \right| \quad (3)$$

$$\text{Metric III} = \sum_{j=1}^N \frac{\sum_{i=1}^N \left| \frac{H_D(f_i) - H_I(f_i)}{H_I(f_i)} \right|}{f_j - f_0} \quad (4)$$

where H_I and H_D represent the magnitude of the FRF for the intact and damaged structure, respectively; f_0 is the lower frequency and f_c is the upper frequency of the range of interest; Δf is the frequency increment between measurement points; and N is the total number of points in the FRF, which depends on both the sampling frequency and the range of interest. All these damage metrics return zero values if there is no change in the FRF of the structure and will return values greater than zero for any change in the vibrational response of the component under analysis.

Using the damage metrics described above, a damage index was calculated for four selected points of the plate (identified as H18, H29, H38, and H40). A frequency range from 15 Hz to 200 Hz was used in the calculations. It is important to notice that while metrics I and II produce dimensionless results, metric III produce indexes that have dimension of 1/Hz. The results are compiled in Table 6:

Table 6 – Damage Indexes obtained experimentally for four selected points of the plate and for three different damage levels.

		H18	H29	H38	H40
Damage Level 1	Metric I	0.4256	0.3671	0.3086	0.3323
	Metric II	0.3210	0.2081	0.1298	0.1413
	Metric III [1/Hz]	0.6823E+4	0.4423E+4	0.2760E+4	0.3002E+4
Damage Level 2	Metric I	0.4076	0.5876	0.4435	0.3501
	Metric II	0.5831	0.4135	0.3070	0.2544
	Metric III [1/Hz]	1.2396E+4	0.8791E+4	0.6527E+4	0.5404E+4
Damage Level 3	Metric I	1.1301	1.4705	1.1124	1.3372
	Metric II	3.3600	1.9909	1.3544	1.4615
	Metric III [1/Hz]	7.1451E+4	4.2338E+4	2.8802E+4	3.1080E+4

In order to better understand how the damage indexes evolve, Fig. 8 below shows a plot of the damage indexes for points H18 and H29 normalized by the first value of the index (i.e. the value of the damage index for Damage Level 1 is set to unity for all the metrics).

As it can be observed from Fig. 8, the values obtained from Metrics II and III evolve almost identically, both showing a higher tendency to increase as damage levels increase when compared to Metric I. When damage increase from Level 1 ($L_c = 30 \text{ mm}$) to Level 2 ($L_c = 60 \text{ mm}$), both metrics II and III show a consistently increase in damage index values for all the points, whilst Metric I displayed a higher value for point H29 and even a slight reduction in the damage index for point H18. When damage was increased to Level 3 ($L_c = 90 \text{ mm}$) all metrics displayed a significant increase in damage index, but the effect was even more evident for Metrics II and III.

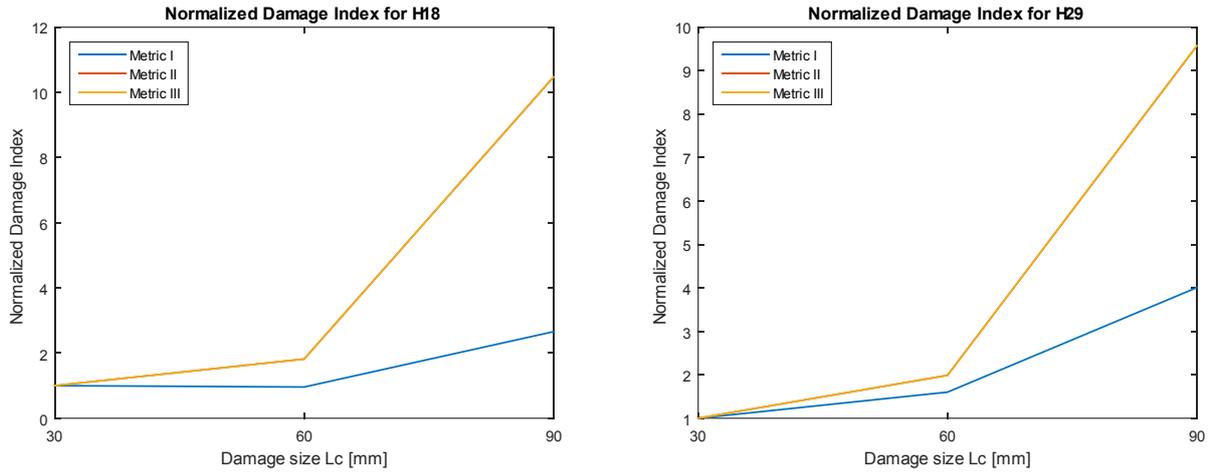


Figure 8 – Normalized damage indexes for points H18 and H29 (experimental analysis).

Table 7 shows the numerical indexes obtained via FEA for the same set of points. Critical damping factors obtained experimentally were used in the simulation, and the FRFs were also evaluated in the same frequency range from 15 Hz to 200 Hz (all FRFs from experimental and numerical analyses had the same frequency increment of 0.25 Hz).

Table 7 – Numerical Damage Indexes for four selected points of the plate and for three different damage levels.

		H18	H29	H38	H40
Damage Level 1	Metric I	0.1835	0.1261	0.1685	0.1880
	Metric II	0.0951	0.0955	0.0686	0.1113
	Metric III [1/Hz]	0.2023E+4	0.2030E+4	0.1460E+4	0.2367E+4
Damage Level 2	Metric I	0.8504	0.8929	0.8384	0.9301
	Metric II	0.8114	0.7652	0.6766	1.0675
	Metric III [1/Hz]	1.7256E+4	1.6274E+4	1.4390E+4	2.2702E+4
Damage Level 3	Metric I	1.4761	1.8266	1.3677	1.6683
	Metric II	4.1048	2.6200	2.1140	2.8148
	Metric III [1/Hz]	8.7292E+4	5.5717E+4	4.4957E+4	5.9860E+4

When comparing the damage indexes from Tables 6 and 7, it can be observed that for Damage Level 1 the results from the numerical simulation are all smaller than the indexes obtained from the experimental analysis. This may be due to the fact that for small levels of damage noise and scatter may have an important contribution in the damage index obtained experimentally, which doesn't show in the numerical analysis. However, for damage levels 2 and 3 the numerical damage indexes are higher than the ones obtained experimentally, for all damage metrics.

Figure 9 below shows the normalized damage indexes for points H18 and H29 obtained in the numerical analysis. Again, it can be observed that Metrics II and III increase more rapidly as damage increases, whilst Metric I increase almost linearly as damage intensifies.

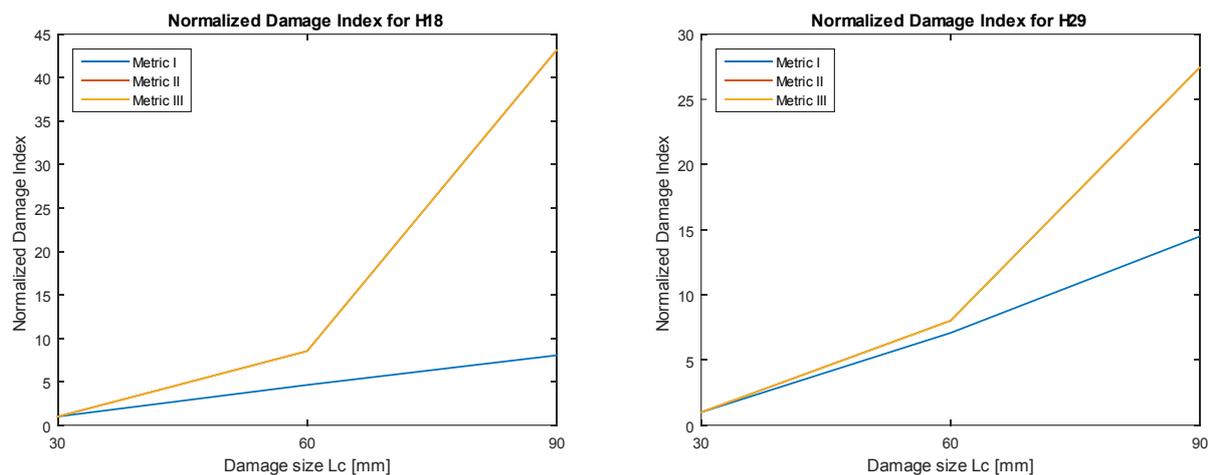


Figure 9 - Normalized damage indexes for points H18 and H29 (numerical analysis).

CONCLUSIONS

The present work investigated how the modal response of a CFRP with thermoplastic matrix vary under the influence of uncertainties in its elastic properties. It was shown that these uncertainties, which may arise during manufacturing processes, for instance, can affect the FRF of the structure and may interfere with SHM systems that are based on vibrational methods. The data from the sensitivity analysis was used to create an envelope for the estimate FRF of the actual plate, and the FRF obtained experimentally was compared with its expected envelope. The curves show a good agreement; however, it was possible to observe that the magnitude of the experimental FRF was higher than the computational results.

The experimental modal analysis of the plate in its damage condition compared to its pristine state show that for the first two levels of damage the shifts in the natural frequency were small, and the same trend was observed when the FRFs were compared, showing the need of damage metrics to help quantify the damage. For this purpose, three different metrics were evaluated, and metrics II and III were the ones that demonstrated a higher sensibility to damage. The comparison between the damage indexes obtained experimentally and the ones obtained via FEA showed that for the lowest level of damage the experimental analysis produced higher values of damage index. This behavior was flipped for damage levels 2 and 3, when the numerical results displayed a higher value of damage indexes, indicating that the numerical model was more sensitive to damage than it was observed in the real structure.

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