Numerical Modeling of a Reinforced Concrete Beam's Vibration

Modelagem Numérica da Vibração de uma Viga de Concreto Armado

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ABSTRACT

Structural Health Monitoring (SHM) can be vastly used to verify the state of a structure, avoiding the need of destructive tests to do so. One of the many ways to perform SHM is by obtaining and evaluating modal parameters (natural frequencies and mode shapes) of a certain structure, collected by dynamic tests, and compare them to pre-estabilished values for non-damaged structures. Such monitoring can be performed with a reduced maintenance cost in the electricity distribution network, which presents a high number of reinforced concrete (RC) light poles. This paper is part of a program that seeks to develop a methodology of structural health monitoring of reinforced concrete light poles using experimental modal analysis (EMA), and since one of the first steps for this is the validation of the structural model, it intends to design a numerical model in a Finite Element (FE) software (ANSYS) of a laboratory tested reinforced concrete beam, and compare the modal parameters numerically, experimentally and analitically obtained. The model considers the behaviour of reinfored concrete, a composite material, and the free-free boundary conditions identical to the ones used in the laboratory tests. The comparative results between the numerical models and experimental tests are satisfatory in such way that they validate the model as proper in the attainment of reinforced concrete light poles's modal parameters.

Key words: Structural Health Monitoring, Finite Element, Reinforced Concrete, Modal Analysis, Vibration.

RESUMO

O Monitoramento da Saúde Estrutural (da sigla em inglês, SHM) pode ser vastamente utilizado para verificar o estado de uma estrutura, evitando a necessidade da utilização de testes destrutivos. Uma das diversas maneiras de se efetuar um SHM é obtendo e avaliando os parâmetros modais (frequências e modos naturais de vibração) de uma determinada estrutura, coletados por testes dinâmicos, e compará-los com valores pré-estabelecidos para estruturas não danificadas. Este monitoramento pode ser feito com um baixo custo na rede de distribuição de energia elétrica, onde se encontra um grande número de postes de concreto armado. Este trabalho é parte de um programa que busca desenvolver um método de SHM de postes de concreto armado utilizando a análise modal, e como um dos primeiros passos para isso é a validação do modelo estrutural, objetiva-se criar um modelo numérico em um software (ANSYS) de Elementos Finitos (FE) de uma viga de concreto armado testa em laboratório, e comparar os parâmetros modais obtidos numérica, analítica e experimentalmente. O modelo considera o comportamento do concreto armado, um material compósito, e uma condição de apoio livre-livre, semelhante à condição na qual a viga foi testada em laboratório. Os resultados comparativos entre o modelo numérico e os testes experimentais são satisfatórios de tal maneira que eles validam o modelo, julgando-o apropriado para a aquisição dos parâmetros modais de postes distribuição de energia elétrica feitos de concreto armado.

Palavras-chave: Monitoramento da Saúde Estrutural, Elementos Finitos, Concreto Armado, Análise Modal, Vibração.

1 INTRODUCTION

During the last few years, some private energy supplying groups in Brazil have been suffering several and serious accidents related to its reinforced concrete light poles, which have been presenting failure during the execution of periodic maintenance. Through the reports presented by the companies themselves, a preliminary risk analysis has been made to guarantee that the execution of such services is safe. Despite that, even though the protocol was followed, there were some signals that the structure was damaged which were not noticed, resulting on its failure and ruin. There were also situations in which the structure seemed to be integer, but when the employee started climbing the pole, it would fail in points underneath the ground.

Among all other maintenance types, the predictive maintenance, which monitors equipment and structures so that early diagnosis and prognosis of defects and damage, is the one that has presented the best cost-benefit (Silva, Rodrigues, Dias, & Brito, 2019).

Being that said, it became necessary to start monitoring the structural health of the light poles in a non-visual manner, similarly to what was done by Oliveira, Chavarette, & Lima (2020). According to Zong, Lin, & Niu (2015), in the practice of Engineering, the approximation between statistical analysis and the structural evaluation is a tendency in the future. Because of that, the study of Engineering problems depends even more in mathematical and computational models, instead of empiric and expensive evaluations.

Similar to what has been done by Figueiredo, et al. (2020), but considering a free-free boundary condition, the main objective of this paper is to compare analytical and computational models, which have been designed in ANSYS, allowing the evaluation of the integrity of reinforced concrete prototypes through dynamic tests, and comparing its results with the ones executed in laboratories.

2 FIRST MODEL: HOMOGENEOUS MATERIAL, FREE-FREE BEAM

To perform a computational modeling using Finite Element software, the first step taken was to create a simple beam model, with a homogeneous material, a constant square-shaped cross section throughout the whole extension of the structure, and having a Free-Free boundary condition, which means the structure is able to move freely, without any supports. This model was designed in ANSYS Workbench, using the material and geometrical properties shown in Table 1 and Table 2.

Table 1 - Material Properties

Young’s Modulus (E)	200 GPa
Shear Modulus (G)	76.9 GPa
Density (ρ)	7850 kg/m³
Poisson’s Ratio (v)	0.3

Source: Elaborated by the authors

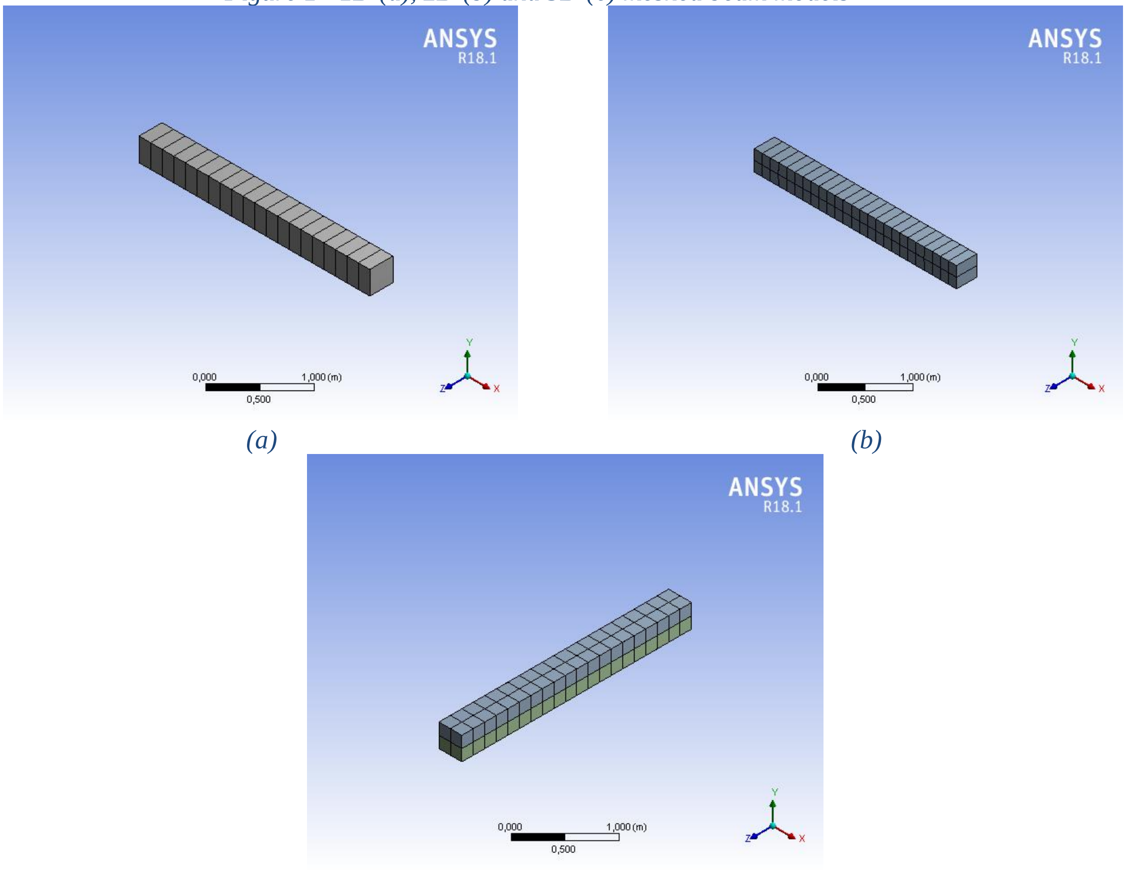
Table 2 - Geometrical Properties of the Beam

Cross Section Height (h)	0.3 m
Cross Section Width (b)	0.3 m
Area (A)	0.09 m²
Moment of Inertia (I)	6.75e-4 m^4
Polar Moment of Inertia (J)	1.35e-3 m^4
Length (L)	5.0 m

Source: Elaborated by the authors

Using the Modal analysis system in ANSYS Workbench, three different models have been designed, with the intention to verify the variations in the results comparing models with one, two, or three dimensions. Figure 1 shows the meshed one-, two- and three-dimensional models, composed by 15-cm-long BEAM188 elements.

Figure 1 - 1D (a), 2D (b) and 3D (c) meshed beam models



(a) *(b)*

(c)

Source: Elaborated by the authors

Having the computational model results been obtained, it was necessary to validate the data with a mathematical model. According to Clough & Penzien (2003), Meirovitch (2001) and J.L.Humar (2001), the equations used to calculate the natural vibration frequencies (ω) of the theoretical Euler-Bernoulli beam are written as follows, being Equations (1), (2) and (3) used to determine the first three flexural vibration frequencies of the free-free beam. The equations (4) and (5) were used to calculate the torsional and axial vibration frequencies of the beam, respectively.

$$\omega_{f1} = \frac{(4.73)^2}{L^2}\sqrt{\frac{EI}{\rho A}} \qquad (1)$$

$$\omega_{f2} = \frac{(7.853)^2}{L^2}\sqrt{\frac{EI}{\rho A}} \qquad (2)$$

$$\omega_{f3} = \frac{(10.996)^2}{L^2}\sqrt{\frac{EI}{\rho A}} \qquad (3)$$

$$\omega_{tn} = \frac{n\pi}{L}\sqrt{\frac{G}{\rho}} \qquad (4)$$

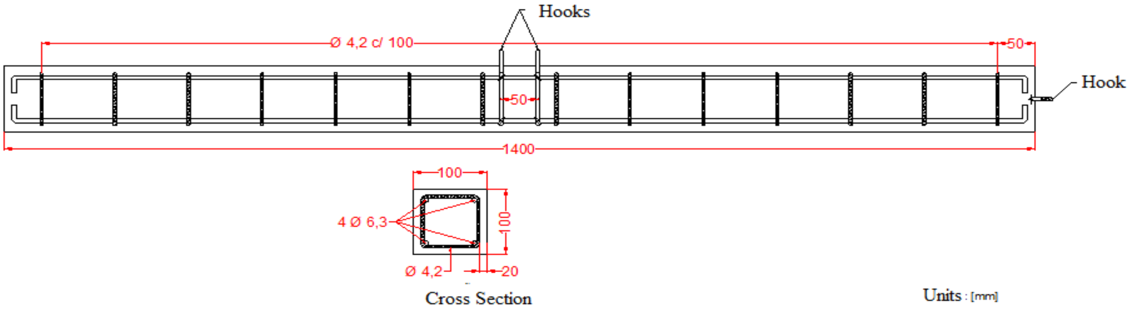
$$\omega_{an} = \frac{n\pi}{L}\sqrt{\frac{E}{\rho}} \qquad (5)$$

3 REINFORCED CONCRETE (RC) BEAM ANSYS AND EXPERIMENTAL MODELS

In order to perform a Structural Health Monitoring of the light poles, it is necessary to have a calibrated and trustworthy computational model that calculates accurately the structure’s natural vibration frequencies. To design a model, several parameters and considerations need to be done, such as elastic supports, non-constant cross-section, damage and reinforced concrete material.

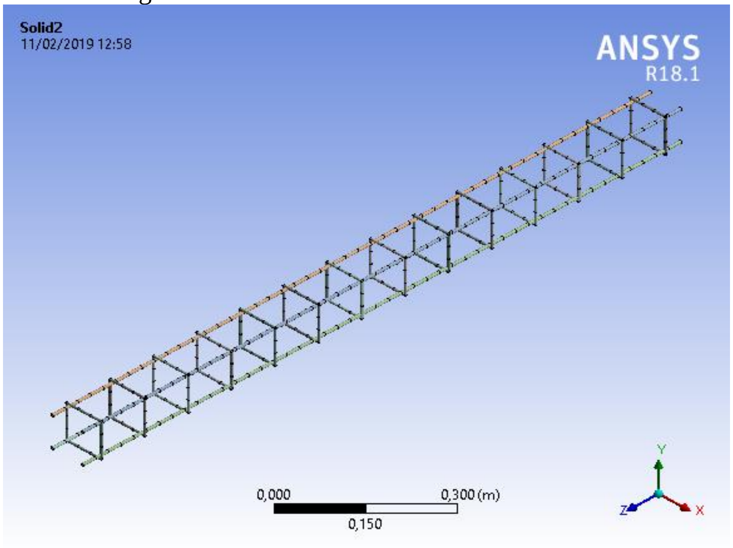
The beam models (both experimental and computational, shown in Figure 2 and Figure 3, respectively) have a 1.40 m length, 10 x 10 cm cross-section, fourteen stirrups, four reinforcement bars. The two central and the extremity hook were used to lift the beam during experimental testing, which can be seen in Figure 4. The mechanical properties of the concrete are shown in Table 3, and were obtained through laboratory tests, done in concrete cylinders (300 mm height and 150 mm diameter), while the rebar properties are shown in Table 4.

Figure 2 - RC Beam project



Source: Elaborated by the authors

Figure 3 – Meshed steel bars in ANSYS model



Source: Elaborated by the authors

Figure 4 - Experimental testing of the beam

Source: Elaborated by the authors

Table 3 - Mechanical properties of the concrete

Young's Modulus (E)	34.7 GPa
Density (ρ)	2289 kg/m³
Poisson's Ratio (ν)	0.2

Source: Elaborated by the authors

Table 4 - Mechanical properties of the rebars

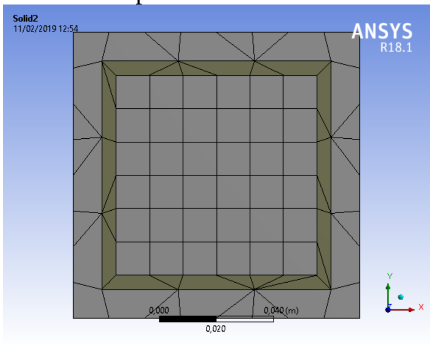
Young's Modulus (E)	200 GPa
Density (ρ)	7850 kg/m³
Poisson's Ratio (ν)	0.3

Source: Elaborated by the authors

Creating the characteristics of RC in ANSYS is complex, since Workbench doesn't have the feature to create a composite material (concrete and reinforcement steel bars) on its Engineering Data, so the material properties had to be implemented by using a specific technique, which consists in separating the concrete portions of the beam in three different parts, shown in Figure 5, and placing the rebars in the interface between each portion, as can be seen in Figure 6.

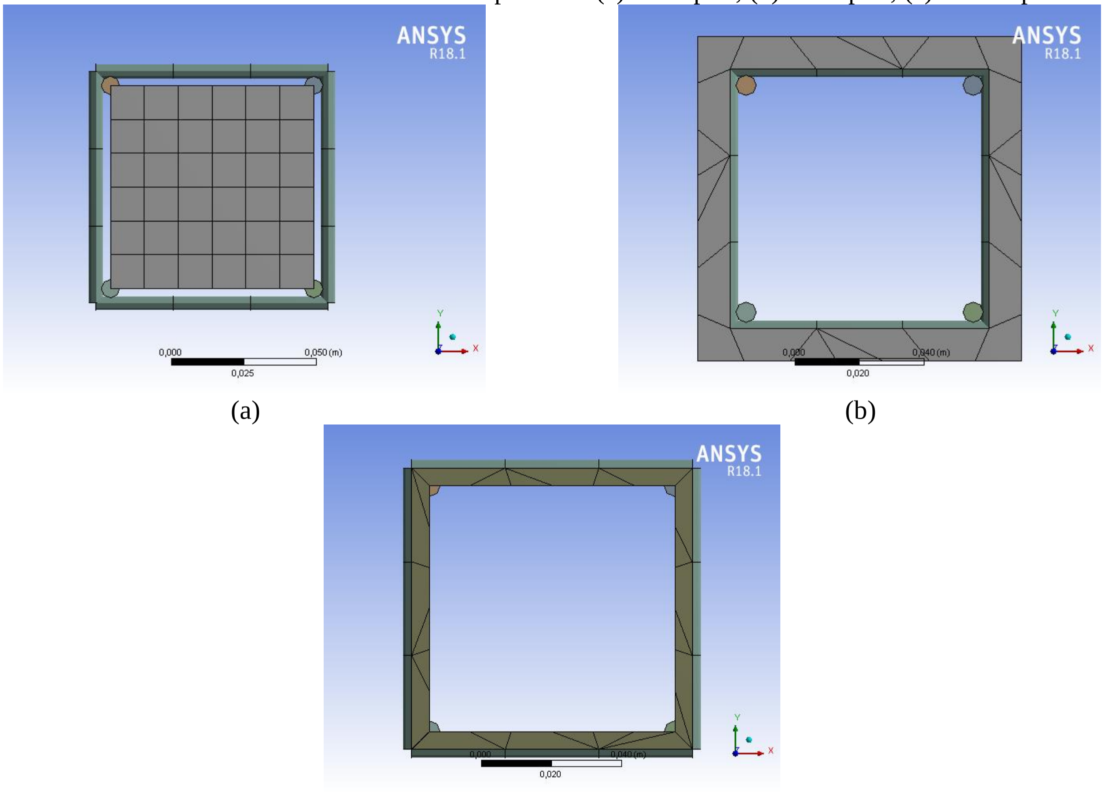
Doing this enables the software to link the Degrees of Freedom (DoF) of the rebar and concrete elements, thus resulting in both materials to behave as a single composite material. The element chosen to represent the concrete was SOLID186, a solid element with 20 nodes, each with three DoFs, being them the translation in the x, y and z axis. A total of 4361 SOLID186 elements were used. Regarding the rebars, the element chosen to represent the steel was BEAM189, a tri-dimensional beam element with six DoFs, being them the translations in the *x*, *y* and *z* axes, and the rotation around these axes. A total of 356 BEAM189 elements were used.

Figure 5 - Concrete portions in the beam's cross-section



Source: Elaborated by the authors

Figure 6 - Rebars on the interface of the concrete portions: (a) inner part; (b) outer part; (c) middle part



(a)

(b)

(c)

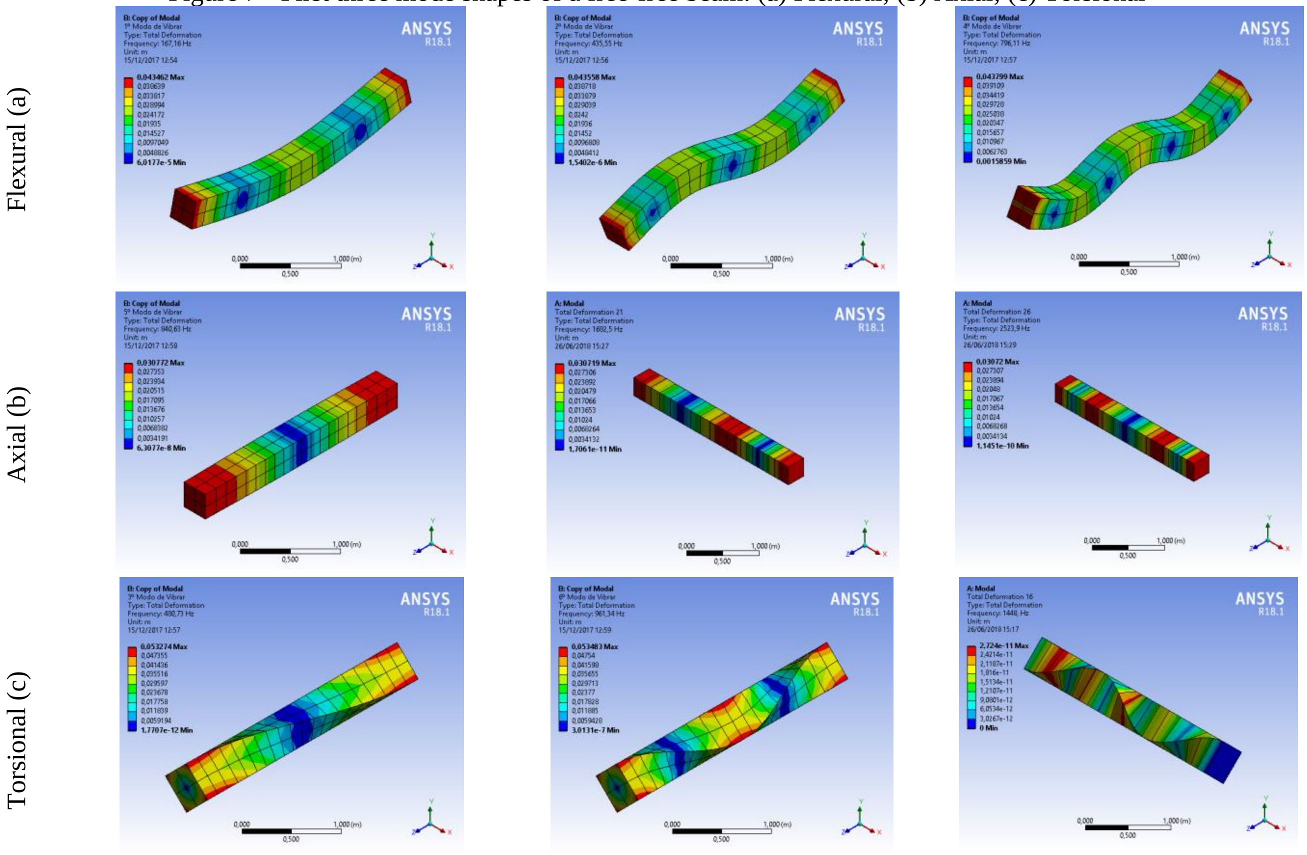
Source: Elaborated by the authors

4 RESULTS AND DISCUSSION

The mode shapes of the beam are shown in Figure 7. Since the cross-section is square-shaped and its dimensions are constant throughout the length of the beam, the flexural modes are actually doubled, having two equal natural frequencies for each one of these modes, on for each axis of inertia. The results of the comparison between the analytical and the numerical models of the free-free standard beam are shown in Table 5.

It is clear to see that the axial frequencies have great accuracy, while the torsional data shows an error pattern throughout the modes. Regarding the flexural natural frequencies, it's noticeable that the error between the models becomes constantly bigger for each mode, which is expected, due to imprecisions present in FE models.

Figure 7 - First three mode shapes of a free-free beam: (a) Flexural; (b) Axial; (c) Torsional



Source: Elaborated by the authors

Table 5 - Natural frequencies of the free-free beam

Vibration Type	Mode	Analytical Frequency [Hz]	1D		2D		3D	
			Hz	Error	Hz	Error	Hz	Error
Flexural	1	62.26	61.47	1.28%	61.55	1.14%	61.48	1.25%
	2	171.62	165.58	3.52%	166.44	3.02%	165.73	3.43%
	3	336.48	314.56	6.51%	317.94	5.51%	315.12	6.35%
Torsional	1	313.04	289.58	7.49%	298.58	4.62%	288.60	7.81%
	2	626.07	579.16	7.49%	597.86	4.51%	577.18	7.81%
	3	939.11	868.75	7.49%	898.54	4.32%	865.74	7.81%
Axial	1	504.75	504.75	0.00%	504.89	-0.03%	504.62	0.03%
	2	1009.51	1009.50	0.00%	1010.60	-0.11%	1008.4	0.11%
	3	1514.26	1514.30	0.00%	1518.00	-0.25%	1510.6	0.24%

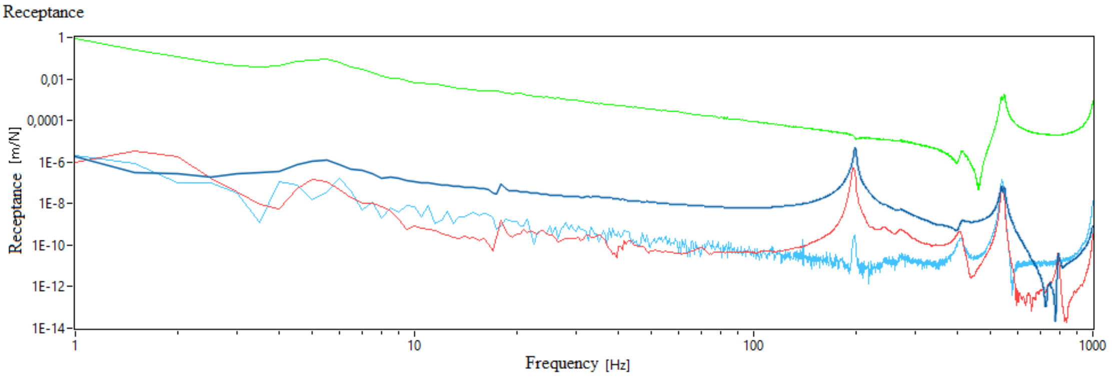
Source: Elaborated by the authors

With these results, it was possible to update the computational model and add RC properties to the material, leading to a comparison with an experimental reinforced concrete beam designed, made and dynamically tested in laboratory.

The experimental tests executed in laboratory acquired the values of the three first natural vibration frequencies of the beam, measured through the beam's receptance shown in Figure 8. The different colors represent four different accelerometers that were installed on the experimental model. It is possible to verify that the first frequency of vibration of the beam is about 214.09 Hz, defined by the first peak in the Receptance curves. Just like the standard beam, the prototype has a square-shaped cross-section, thus resulting in twinned frequencies for each flexural mode shape, so the second natural frequency is 214.09 Hz as well. The second peak indicates a third natural vibration frequency on 591.08 Hz, which is also a flexural mode, thus also having a twinned natural frequency.

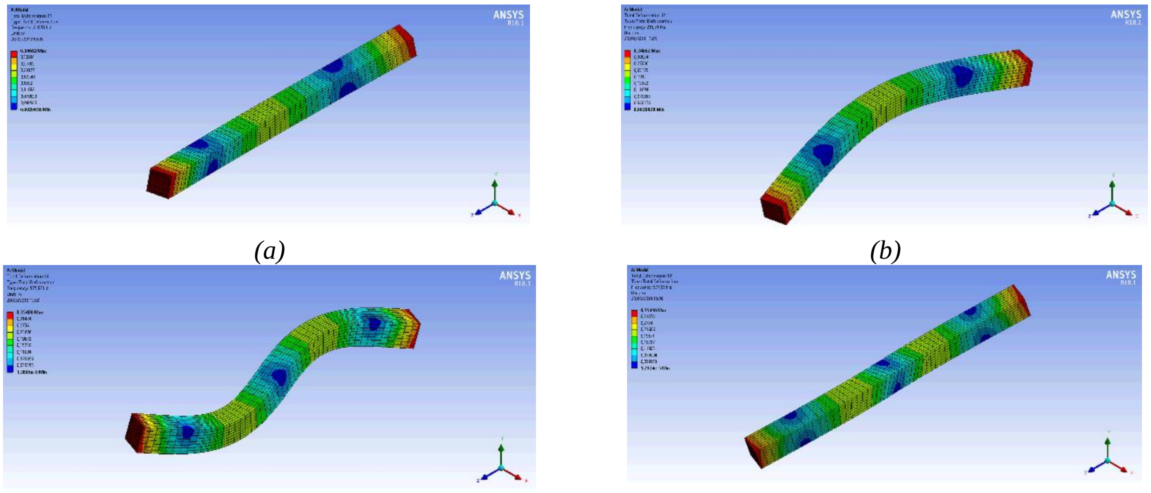
The numerical model presented these exact behaviors in the first four mode shapes, as can be seen in Figure 9. The numerical data of the natural frequencies and the errors when compared to the experimental values are shown in Table 6.

Figure 8 - Receptance of the Reinforced Concrete Beam



Source: Institutos Lactec (2018)

Figure 9 - Mode shapes of the RC prototype: (a) first mode; (b) second mode; (c) third mode; (d) fourth mode



(a) *(b)*

(c) *(d)*

Source: Elaborated by the authors

Table 6 - Natural Frequencies of the beam

Mode	**Natural Frequency [Hz]**		**Error**
	Experimental Analysis **(10/19/2018)**	**Computational Model**	
1(a)	**214.09**	**213.92**	**0.08%**
2(b)	**214.09**	**213.92**	**0.08%**
3(c)	**591.08**	**571.01**	**3.40%**
4(d)	**591.08**	**571.01**	**3.40%**

Source: Elaborated by the authors

According to Zheng, Huo Sharon & Yuan (2008), the dynamic modulus of elasticity (E_d) is higher than the static modulus of elasticity (E), so the computational data was acquired by doing a retro-analysis of the problem. The Young's Module inserted in the numerical model was adjusted in such a way that its first natural frequency was similar to the one obtained from the experimental analysis. This happened when E was set to 38.3 GPa, approximately 10.37% higher than the parameter measured in laboratory, which confirms what was stated by Zheng, Huo Sharon & Yuan (2008).

Similar to the standard beam, the flexural frequencies from the prototype also show increases in the errors in each subsequent mode, due to simplifications and imprecisions of the Finite Element Method (FEM). Apart from that, the results were satisfactory, since the errors were small, so it was considered that the model is trustworthy regarding the representation of the behaviour of a RC beam.

5 CONCLUSION

After analyzing the frequencies obtained from the experimental and computational models, it is possible to claim that the Finite Element has a good accuracy, although it is known that both FE and EMA have their errors and simplifications. One of the following steps is to update the model towards the final desired model, which is a RC pole of distribution, with variable cross-section and elastic support. However, it is important to keep validating the procedures implemented in this current paper by designing new computational models based on non-computational analytical models and comparing the results obtained by each one of them.

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