CONSIDERATIONS ABOUT FREE VIBRATION ON BRIDGES

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Abstract. *Bridges are structures used on routes that allow vehicles to cross obstacles such as rivers. They are built considering the efforts to which they will be submitted and their distribution in the structure. Furthermore, it is necessary to assess their natural frequencies of vibration. In the present study some effects were analyzed related to the vibrations of grid bridges and viaducts resulting from changes in stiffness and mass in these structures. This analysis was made considering that excessive vibrations are not consistent with human comfort and bridge durability. For the structure, it is interesting to get away from the resonance effect, which occurs when the excitation frequency matches one of the natural frequencies of oscillation of the system. This leads to oscillation with increasing amplitudes which may cause even the ruin. In order to study several models, three different design situations were adopted: superstructure with varying heights of beams and crossbeams, from which it was possible to conclude that the height of the beams has more impact on the undamped natural frequency of the structure than the crossbeams; small defects or damage to the structure and the effect of a ruptured beam in which its undamped natural frequencies were compared.*

Keywords: *Bridges, Girders, Crossbeams, Undamped free vibrations, Resonance.*

1 INTRODUCTION

Bridges have a large role in terms of infrastructure advances in Brazil. It is possible to notice a modification in the current designs for the crossbeams. Its use is controversial subject in the dimensioning of bridges. According to Fulgêncio, Paula and Azevedo (2014), the use of girder beams in bridges often requires the use of crossbeams and they require a relevant effort for their execution, because they are usually concreted in loco. Thus, it is necessary to consider the grid effect on the efforts and deformations in time to analyze the project.

In recent years, it has become increasingly common practice to build bridges in reinforced concrete without the presence of crossbeams. Fulgêncio, Paula and Azevedo (2014) concluded, as Alves (2010), that the use of crossbeams, from the point of view of requests and deformations of the bridge, is not considered compensatory. Starting from the hypothesis that statically crossbeams are not necessary, it was sought to discover their influence on the vibrations of the structure, in order to justify its use.

Many bridges were built many years ago and during their lifetime these were sometimes damaged. The accidents considered for this research are those in which a truck, for example, when passing through the route inferior to the bridge, damages the stringer by having more height than is allowed in the way. These accidents cause damage to the structure, which can range from a small part of the cracked concrete to a complete break in the stringer. In order to simulate these damages, different models were made with presence of damages. Each such case has been studied for damage in different positions. It is believed that, with this work, future research, in the field of experimental dynamic analysis, can be encouraged. It is also expected that structures, with resonance problems, are supported to modify project parameters and avoid critical excitation.

2 METHODOLOGY

For this work the case studied is the system with undamped free vibration. Thus, for each mode of interest it is possible to determine the undamped natural frequency, with $c = 0$, which represents the way the undamped structure preferably vibrates.

A serviceability limit state is that of excessive vibrations (Albuquerque; Kramar, 2015). These vibrations are present in most structures and are undesirable because they cause unnecessary movements, noises, dynamic tensions, discomfort and a sense of insecurity for the users.

According to Veloza (2009), we can conceptualize other types of vibrations and explain how modal analysis works. Besides the modal analysis, other possible forms of vibrations are: damped vibrations - with the presence of dissipative forces the system tends to return to its original equilibrium position. It is an oscillating movement around the equilibrium position until rest is reached. Depending on the damping value, if it is too large, vibrations may not occur. Damping, in concrete structures, is considered low, less than 2% for bridges in general, according to Bachmann, Ammann, Deisch (1995) and Pravia and Braido (2016). Because it has such an order of magnitude, it can be neglected in an evaluation of free vibrations. Another way would be forced vibrations - actions due to a periodic or non-periodic action applied to the system. As an analysis of forced vibrations depends on the knowledge of the temporal variation of the loads, and this variation is not explicitly given in the Brazilian norms, it was not possible to define a dynamic load and it was decided to study only free vibrations without damping. In addition, the adopted case characterizes the dynamic properties of the structure, besides being a good indicator of geometric problems and damages in the structure.

To determine the modes of vibration, and therefore understand the behavior of the structure, modal analysis will be used. The number of desired modes can be specified in the program that will be used for calculation.

These modes can then be used as the basis for a modal superposition in the cases of analysis for a response-spectrum, which relates the dynamic characteristics of the structure, defined by its own frequency and by the damping coefficient with the peak of the response of the structure to that action (Teixeira, 2010).

A time-history modal can also be made, a step-by-step dynamic structure response due to a specified load which can vary over time. It can be done by numerical integration or modal superposition (Lima, 2013).

The so-called transient dynamic analysis, used to find the response of a structure to the arbitrary and time-varying load (Marinho, 2002), can also be performed.

Two methods of modal analysis are: Eigenvector that determines the free and non-damped modes of vibration and the system and Ritz-vector that take into account the spatial distribution of dynamic loading, while the direct use of natural-mode formats neglects this information. From the description of Clough And Penzien (2003), he tries to find the modes of vibration excited by a particular charge.

The modal analysis is always linear. A case of modal analysis may be based on the rigidity of the entire unloaded structure, or on the stiffness of the end of the analysis of a non-linear case.

In bridges, nonlinear analysis is common in tall, thin, with large spans, suspension bridge and cable-stayed bridge. A first order analysis is usually adequate for short and medium spans (Akkari, Duan, 2000). Thus, the effects of non-linearity will not be object of study in the present work.

To reach the proposed objectives the following methodology was applied:

a) Grid bridge modeling, with two crossbeams, in the SAP 2000; Dynamic analysis of a structure can be done in different ways. For the present paper, it will be done through computer software, SAP2000, based on its Manual (2011).

b) Calculation of the first two modes of undamped natural frequency of the bridge, varying heights of transverse and longitudinal members and comparing them.

c) Simulation of the structure with a damaged stringer, with damaged dimension arbitrarily adopted of 30x50cm. The undamped natural frequency of each stringer was studied.

d) Comparison of the modes of the two cases above, intact structure and damaged.

2.1 "Intact" Model With Two Crossbeams

Initially, the model had two intermediate crossbeams, according to Figure 1. It was called intact the model that does not have geometric imperfections.

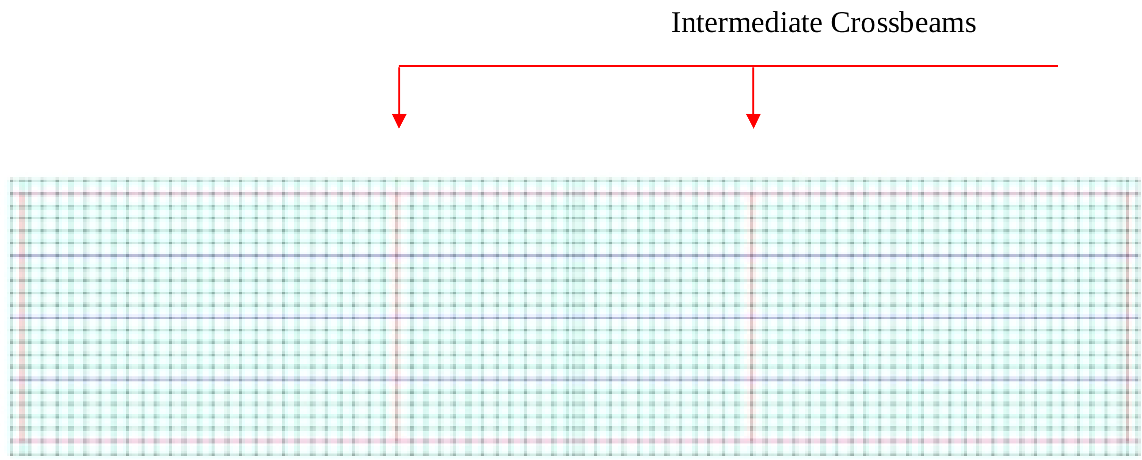

Figure 1 - SAP2000 model with two intermediate crossbeams.

2.2 "Damaged" Model With Two Crossbeams - Reducing An Element

Initially, the model had two intermediate crossbeams elements in the SAP2000 program, separating it in spans 1,2 and 3. Simulating imperfections in the stringer were introduced in the "damage" model, in this case, arbitrarily reducing in 30 cm the height Of the stringer in a 50cm band, as shown below.

The location of the damage can be seen in Figure 2, and was the same one adopted in the previous case with the intention of comparing them. The height adopted for the part of the simulated stringer as damaged was 1.7m.

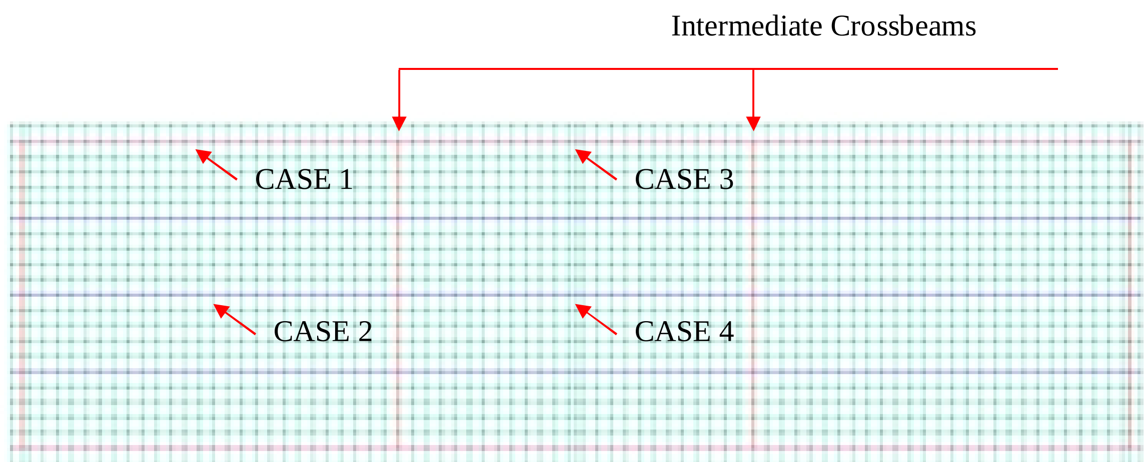

Figure 2 - Location of reduced stringers.

CASE 1: External stringer with a 30cm height reduction in span 1 or 3;

CASE 2: Internal stringer with a 30cm height reduction in span 1 or 3;

CASE 3: External stringer with a 30cm height reduction in span 2;

CASE 4: Internal stringer with a 30cm height reduction in the span 2.

2.3 Vibration Modes

The two modes that will be analyzed are the first two modes of vibration of the structure, the first mode is the bending mode and the second mode is the twist mode.

The vibration modes of a structure are ordered by frequency (Clough And Penzien, 2003). It is possible to justify the choice to analyze only the first two modes as follows: excitations are generally of low frequency, (Brasil And Silva, 2013), typically bridge frequencies are of the order of 2 to 4 Hz (Bachmann, Ammann, Deisch, 1995) and the first modes have lower frequency, lower energy and rigidity, and therefore are more susceptible to excitations, leading to local deformations and, consequently, inherent structural weaknesses (Kurowski, P., Kurowski, T., 2009);

First mode. The first mode is a bending mode, as can be seen in Figure 3.

Figure 3 - First mode.

For this model the undamped natural frequency of the first mode was removed from the program for varying heights of stringers. The variation occurred from 1.75m to 2.65m, every 15cm.

Similarly the process was done for the crossbeams.

Second mode. In the second mode, shown in Figure 4, there was also torsion:

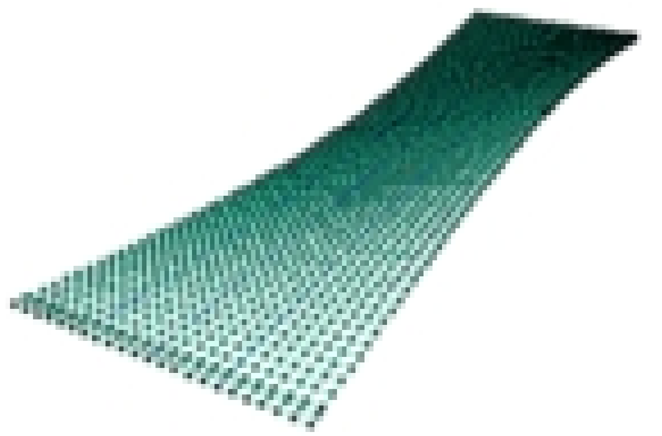

Figure 4 - SAP2000 model of the second mode with torsion.

There were also varied heights of stringers. The variation occurred from 1.75m to 2.65m, every 15cm.

Similarly the process was done for the crossbeaams.

3 RESULTS ANALYSIS

Results analysis based on graphs and graphs comparing undamped natural frequencies.

3.1 "Intact" Model With Two Crossbeams

First mode. With an arbitrary fixed height of 1.75 m in the crossbeams the height of the stringer was varied adopting 2.2 m as an initial height. The undamped natural frequencies and respective periods obtained are presented in Table 1 and graphically in Figure 5.

The undamped natural frequency obtained for each stringer was compared to the one with 2.2m, the value adopted as the base, with the intention of knowing how many percent the 15cm in height influence the undamped natural frequency.

Table 1 - Undamped natural frequencies obtained by varying the stringers.

Crossbeam Height (m)	Beam Height (m)	T (s)	f (Hz)	T %	f %
	1,75	0,623	1,606	29,863	-22,995
	1,90	0,566	1,766	18,080	-15,311
	2,05	0,519	1,926	8,276	-7,644
1,75	**2,20**	**0,479**	**2,086**	0,000	0,000
	2,35	0,446	2,245	-7,077	7,616
	2,50	0,416	2,403	-13,195	15,202
	2,65	0,391	2,560	-18,537	22,754

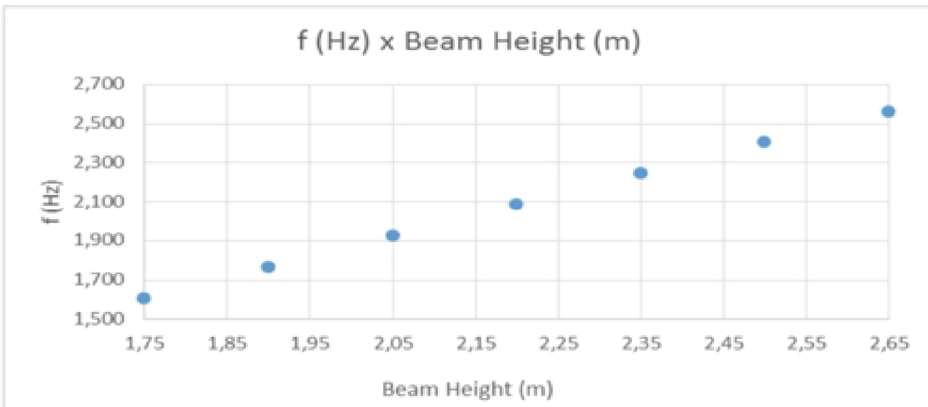

Figure 5 - Undamped natural in function of the variation of the stringers.

The result is coherent, because changing the vertical dimension of the stringer modifies the mass and rigidity. The proportion is linear with the mass and cubic with the rigidity, causing great impact on the result. The opposite occurs when changing the dimensions of the crossbeams as can be seen next.

Then, the results are shown with the stringer with the fixed height of 2.2 m and the crossbeams with 1,75 m height, also changed every 15 cm. The results obtained are shown in Table 2 and Figure 6 below.

Table 2 - Undamped natural frequencies obtained by varying the crossbeams.

Crossbeam Height (m)	Beam Height (m)	T (s)	f (Hz)	T %	f %
1,30		0,477	2,097	-0,521	0,524
1,45		0,478	2,093	-0,348	0,349
1,60		0,479	2,089	-0,173	0,175
1,75	**2,2**	**0,479**	**2,086**	0,000	0,000
1,90		0,480	2,082	0,175	-0,174
2,05		0,481	2,079	0,348	-0,348
2,20		0,482	2,075	0,524	-0,521

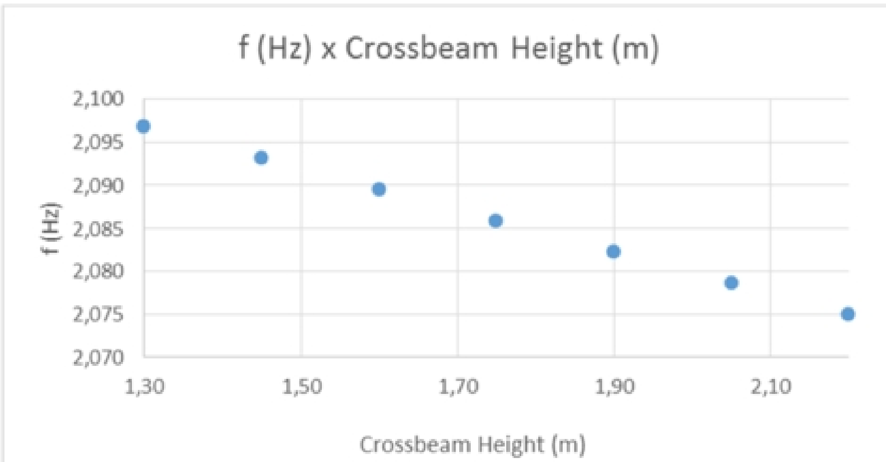

Figure 6 - Undamped natural frequency by varying the crossbeams.

With the graph it is possible to visualize that with the increase of the height of the crossbeams the natural frequencies without damping suffer a very soft fall, approximately every 15cm that increases the frequency falls 0.17%. With this, we can conclude that the crossbeams little interfere in the vibration of the structure, in the first mode.

Second mode. Similarly the whole process was done for the second mode. The undamped natural frequencies obtained are presented in Table 3 and Figure 7 with variation of height of stringers.

Table 3 - Undamped natural frequencies obtained by varying the stringers.

Crossbeam Height (m)	Beam Height (m)	T (s)	f (Hz)	T %	f %
	1,75	0,505	1,979	21,163	-17,507
	1,90	0,472	2,116	13,189	-11,797
	2,05	0,443	2,257	6,235	-5,919
1,75	**2,20**	**0,417**	**2,399**	0,000	0,000
	2,35	0,393	2,543	-5,875	6,003
	2,50	0,372	2,688	-10,791	12,043
	2,65	0,353	2,833	-15,348	18,091

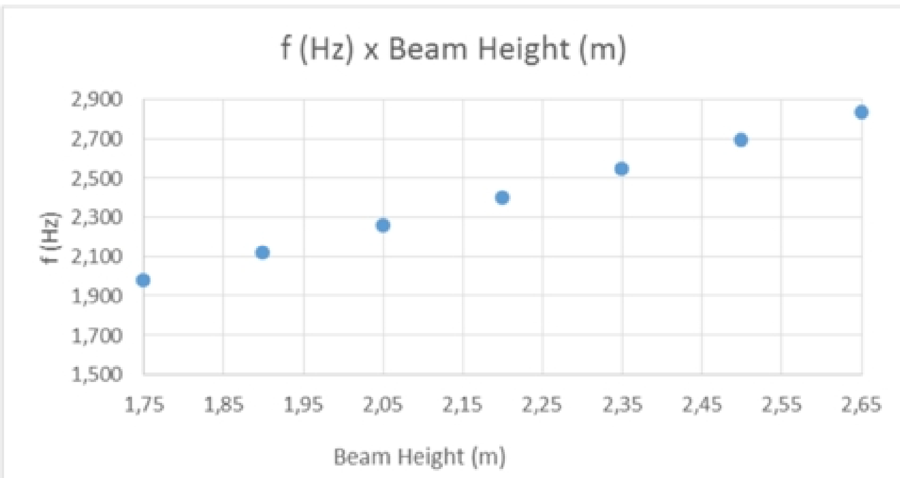

Figure 7 - Undamped natural frequency due to the variation of the stringers.

In the chart it is possible to see the variation of the natural frequency undamped in function of the stringers. The result was expected, because altering the stringer dimension modifies the mass and stiffness, as commented.

The results are then presented for the variation of the crossbeams heights. The undamped natural frequencies obtained are shown in Table 4 and Figure 8.

Table 4 - Undamped natural frequencies obtained by varying the crossbeams.

Crossbeam Height (m)	Beam Height (m)	T (s)	f (Hz)	T %	f %
1,30		0,41595	2,404	-0,216	0,208
1,45		0,41621	2,402	-0,154	0,125
1,60		0,41652	2,401	-0,079	0,083
1,75	**2,2**	**0,41685**	**2,399**	0,000	0,000
1,90		0,41721	2,397	0,086	-0,083
2,05		0,41758	2,395	0,175	-0,167
2,20		0,41796	2,393	0,266	-0,250

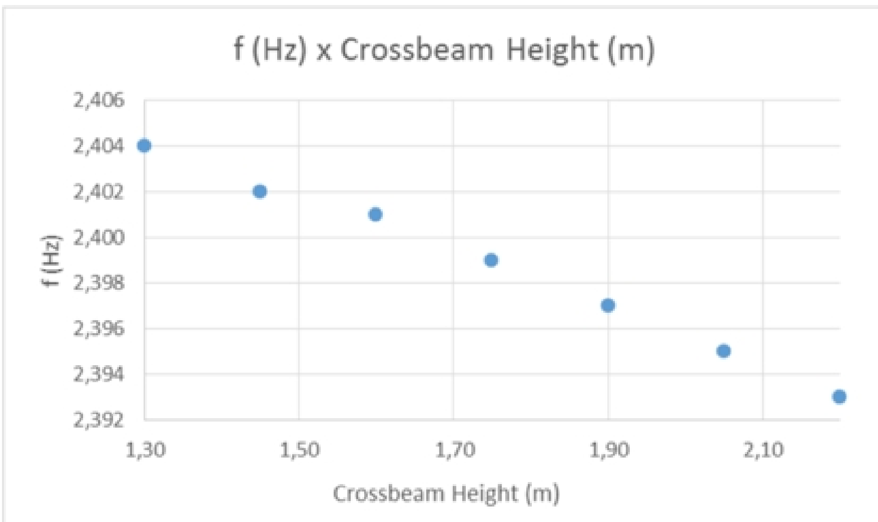

Figure 8 - Undamped natural frequency as a function of the crossbeams variation.

The crossbeams, therefore, does not appear to substantially affect this second mode.

3.2 "Damaged" Model With Two Crossbeams - Reducing An Element

The two modes were compared according to Table 5. The CASES compared are defined in Figure 2.

Table 5 - Comparison of studied modes.

REDUCING ELEMENT

1º MODE

Model	Crossbeam Height (m)	Beam Height (m)	T (s)	f (Hz)	T %	f %
"Intact"	**1,75**	**2,2**	0,480	2,082	0,000	0,000
"Damaged" CASE 1		**1,7**	0,481	2,081	0,123	-0,027
"Damaged" CASE 2			0,481	2,080	0,058	-0,058
"Damaged" CASE 3			0,481	2,077	0,210	-0,209
"Damaged" CASE 4			0,482	2,077	0,229	-0,229

2º MODE

MODEL	Crossbeam Height (m)	Beam Height (m)	T (s)	f (Hz)	T %	f %
"Intact"	**1,75**	**2,2**	0,417	2,399	0,000	0,000
"Damaged" CASE 1		**1,7**	0,417	2,400	0,000	0,029
"Damaged" CASE 2			0,417	2,399	-0,034	-0,005
"Damaged" CASE 3			0,418	2,392	0,273	-0,312
"Damaged" CASE 4			0,417	2,399	-0,036	-0,003

Note that the first mode also presented higher frequency variations than the second. It has also been found that imperfections in the stringer in the edge produce higher vibrations in the structure. It is also possible to check the vibration percentage over the structure and again compare it to the intact model.

4 FINAL COMMENTS

With the evolution of the road demand, the bridges needed to support more and more load and for this, a greater expense with materials becomes necessary. Bridges with stringers are the most used and intermediate crossbeams often appear, especially in older works of art. The present work seeks to demonstrate that the use of crossbeams would result in a considerable reduction in vibrations, stimulating its use in bridge projects.

Nowadays, most of the bridges are built without intermediary crossbeams, because their execution is not always advantageous, given the constructive and aesthetic disadvantages that these imply.

Comparing the undamped natural frequency of the first and second modes of a bridge by varying the height of its crossbeams no great differences were found. Comparisons were made by varying the undamped natural frequency of a bridge and varying the height of its stringers for the first two modes. The differences verified were much more significant. Therefore, the height of the crossbeams would not be a good parameter to be modified if the intention was to avoid the resonance phenomenon.

The model bridge was tested with the presence of "damages", observing the behavior of four points - in the central and the external spar in different spans and the difference of the undamped natural frequency was verified. It was then decided to reduce the height of these elements for an analysis of a situation more commonly found. Often structures are damaged but not totally ruptured despite the impact.

It is hoped that this work could ease future researches in the field of experimental dynamic analysis, that structures with resonance problems or undamped natural frequencies, can have their project parameters modified and avoid critical excitation.

However, the reverse process is also possible. If a structure with a known undamped natural frequency was monitored and had any known changes in vibration over time, this could indicate a structural damage. This damage could not be located only by the value of the vibration, since the values found did not follow a pattern that would allow it to be described with this precision. But it would already be an index, non-invasive or destructive, indicating that the structure should be surveyed.

5 REFERENCES

Akkari, M., Duan L. *Nonlinear Analysis of Bridge Structures. Bridge Engineering Handbook*. Boca Raton: CRC Press, 2000.

Albuquerque, F. S. C. de; Kramar, W. F. *Análise do comportamento estrutural de uma ponte ferroviária de concreto armado submetida a esforços de natureza dinâmica*. Bacharelado em Engenharia Civil. Universidade Federal Federal do Paraná. Curitiba: UFPR, 2015.

Alves, M. S. *Avaliação da distribuição transversal de cargas em tabuleiros de pontes em vigas múltiplas, com e sem transversinas internas*. Salvador, 2010.

Bachmann, H.; Ammann, W. J.; Deisch. F. *Vibration problems in structures: practical guidelines*. New York: Springer Verlag, 1995.

Brasil, R.; Silva, M. *Introdução à Dinâmica das Estruturas*. São Paulo. Edgard Blucher, 2013.

Clough, R.W.; Penzien, J. *Dynamics of structures*. Berkeley: Computers & Structures, 2003.

Fulgêncio, J. P. T. O. R; Paula, F. A; Azevedo, C. P B. *Análise do Uso de Vigas Transversinas em Pontes de Concreto Armado*. In: VII Congresso Brasileiro de Pontes e Estruturas, 2014.

Lima, G. V. F. *Análise dinâmica via método dos elementos finitos do Estádio Nacional de Brasília*. Dissertação de Mestrado em Estruturas e Construção Civil. Universidade de Brasília. Brasília: UNB, 2013.

Manual For SAP2000. *CSI Analysis Reference Manual for SAP2000*, Computers And Structures, Inc.,ETABS, SAFE and CSiBridge, Berkley, CA, 2011.

Marinho, Ivy J. P. *Projeto Ótimo de Estruturas Metálicas de Arquibancadas Reutilizáveis via ANSYS*. Dissertação de Mestrado em Engenharia Civil. Programa de Pós-Graduação em Engenharia Civil. Rio de Janeiro: PUC, 2002.

Pravia, Z.M.C; Braido, J, D. *Alternativas de medições de vibrações de baixo custo para obras de arte*. IX Congresso Brasileiro de Pontes e Estruturas, 2016.

Teixeira, F. D. *Análise Sísmica de Pontes Análise Conjunta da Estrutura e Fundação*. Dissertação de Mestrado em Engenharia Civil, 2010.

Veloza, L. T. M. *Análise dinâmica de estruturas, utilizando o software SAP 2000*. Graduação em Engenharia Civil. Departamento de Engenharia Civil. Universidade Federal de São Carlos. São Carlos: UFSCAR, 2009.

Kurowski, P. M.; Kurowski, T. P. *Vibration Analysis for Designers,* Machine Design , Design Generator Inc. London. Ontario: Leslie Gordon, 2009.