COBEM 99
XV Congresso Brasileiro de Engenharia Mecânica
15th Brazilian Congress of Mechanical Engineering
22 - 26 de Novembro de 1999 / November 22 - 26, 1999 Águas de Lindóia, São Paulo,

VERIFICATION OF STRUCTURES SUBMITTED TO DYNAMIC OCCUPANCY LOAD

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Abstract. *Modern structures are properly designed to resist static loads, but in some cases, when the structure is very flexible and/or slender, it is necessary to conduct a verification for dynamic loads due to human activities. Footbridges is a practical case where this verification is necessary, where only traffic due to people walking can generate levels of vibrations that are so high that it may be uncomfortable for use, and in some cases, it may compromise structural safety.*

In the need of trying to show the importance of these dynamic loads generated by human activities, this work presents a comparison between results from a static conventional analysis and an analysis that considers dynamic loads. These analyses were conducted for an existing metallic footbridge. From data obtained in the dynamic analysis, it could be observed that the footbridge presents levels of displacements that are superior than the maximum allowed values in Brazilian codes. Afterwards, due to the need of reducing high levels of vibrations presented by the footbridge, a vibration absorption system was designed and a significant reduction of displacements presented by the footbridge was observed.

Key words: *Dynamic Loads, Vibrations, and Absorption System.*

1. INTRODUCTION

Nowadays, there is a need of having slender and more economical structures, due to the expediency in construction, therefore, many structures designed are metallic or mixed structures. Generally, these structures are very slender and flexible, what makes that the values of their first three natural frequencies are less than 5 Hz. Therefore, these structures, mainly metallic footbridges, when submitted to dynamic loading due to human activities may present excessive level of vibrations that, in most cases, even if it does not compromise structural safety, may cause great discomfort. In some extreme cases, this load may generate high levels of tensions and excessive displacements, that may compromise structural safety. This is due to the combination of two factors: low structural natural frequency associated to the fact that human load may be represented by its first three frequency components, that lay in the range 1.5 to 10 Hz. That is, the structure may enter resonance, generating dynamic amplification factors superior than those predicted in structural design codes.

Dynamic loads due to human activities may be separated in two groups: (i) with loss of contact with the structure, for activities such as jumping, running and some types of exercises and dance; (ii) without loss of contact with the structure, that is, walking and some types of dances, being type (i) loads generally greater and more important than loads of group (ii) when verifying structural behavior and safety.

At Prof. Lobo Carneiro's Structures Laboratory, of Civil Engineering Program at COPPE/UFRJ, a research was developed, that had as main goal to mathematically describe, from experimental data, dynamic loads due to several human activities. With the dynamic load models, a verification was made, both for static and dynamic load due to people walking, for an existing metallic footbridge. From results obtained by mathematical modeling and due to high displacements presented by the footbridge, a vibration absorption system was designed, in order to reduce these displacements. Later, an evaluation of the structure to determine the comfort level for users was conducted.

2. MODELLING DYNAMIC HUMAN LOADS

The tests performed for data collecting were made on a rigid platform constructed in reinforced concrete. Initially, this rigid platform was used with the intention of minimizing the interaction between loads due to different types of human activities and the test platform movements. Each individual was asked to perform three activities: walk, run and jump. Force signals obtained for each activity were processed and, time and frequency domain analysis were performed to obtain the parameters that describe these loads.

For jumping activity, besides tests performed on the rigid platform, some tests were performed on a metallic beam, at a pre-determined frequency of 2.00 Hz. These tests were conducted in three situations: original structure and with vibration absorption systems S1 and S2 as described by Rodríguez (1996). The absorption system is a one-degree of freedom system, viscous mass-spring-damper. The mass-spring-damper system where the initial damping value of the absorption system was kept, was named S1; system S2 used the same spring but rubber rings were installed laterally to obtain higher damping values. Table 1 presents damping rates for each case of damper used, S1 and S2.

Table 1- Absorption system: damping rates experimentally obtained.

	Damping Rates (%)
S1	0.85
S2	5.00

Results obtained both from rigid and flexible structure, are shown in Table 2.

Table 2- Comparison between Fourier coefficients for flexible and rigid structure – Jumping activity.

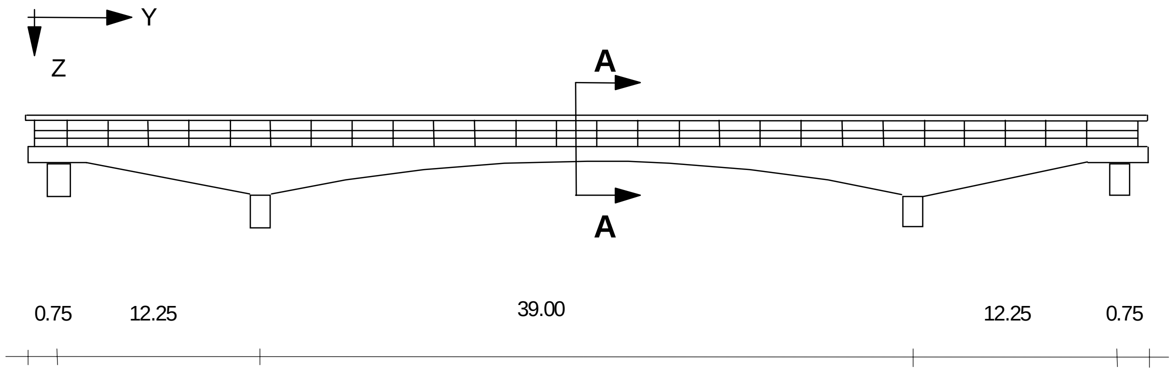
Test type	Mean Values			
	f_1	a_1	a_2	a_3
Original structure (flexible)	2.04	1.47	0.30	0.06
Flexible structure with absorber and damping rate S1	2.00	1.58	0.72	0.12
Flexible structure with absorber and damping rate S2	1.93	1.53	0.56	0.07
Rigid structure	2.00	1.58	0.69	0.14

From Table 2, one can observe that Fourier coefficients obtained for the flexible structure present inferior values than those obtained using the rigid platform and, when an absorption system with S1 damping rate is introduced, the values for these coefficients tend to the ones obtained in the rigid platform. Once the absorption system is introduced, a modification in the structure's natural frequency takes place, raising its modal stiffness and bringing Fourier coefficient values closer to those obtained with the rigid platform.

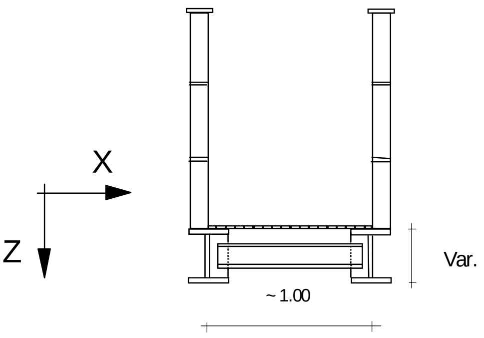
3. DESCRIPTION OF THE FOOTBRIDGE

The footbridge that was chosen for verification, was designed by the Compania Siderúrgica Nacional Metallic Structures Industry, in the year of 1973. It is a metallic footbridge for pedestrian traffic, located over a heavy vehicle traffic avenue, in the city of Rio de Janeiro. This footbridge was made of ASTM-A-36 steel, with admissible stress σ_{adm} = 235 MPa.

Figure 1 shows main dimensions of the footbridge, which is constituted by two I type profiles, connected by steel sleepers and a steel plate that is used as deck. The footbridge was modeled with plane frame elements and subdivided in equally spaced elements of 1m length. The footbridge has variable cross section along its length, with 12 different sections that are shown in Table 3 and Figure 2.



(a) Plant view



(b) View

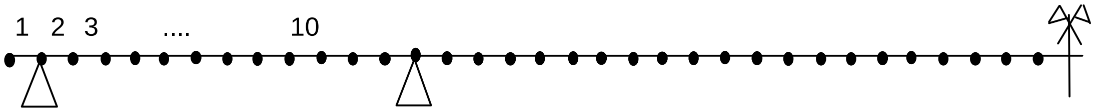
A-A

Units in meters

Figure 1- Design of a metallic footbridge with variable cross section.

Table 3- Characteristics of the footbridge.

Cross section type	Area (m^2)	Inertia $_{z\text{-}z}$ (m^4)
1	1.113×10^{-2}	1.088×10^{-3}
2	8.316×10^{-3}	9.300×10^{-4}
3	9.150×10^{-3}	1.468×10^{-3}
4	9.415×10^{-3}	1.698×10^{-3}
5	1.056×10^{-2}	2.433×10^{-3}
6	1.043×10^{-2}	2.655×10^{-3}
7	1.026×10^{-2}	2.468×10^{-3}
8	9.868×10^{-3}	2.075×10^{-3}
9	9.646×10^{-3}	1.870×10^{-3}
10	9.252×10^{-3}	1.566×10^{-3}
11	8.784×10^{-3}	1.239×10^{-3}
12	9.816×10^{-3}	1.890×10^{-3}



Section type 1 - elements 1 to 6, 26 to 29
Section type 2 - elements 7, 23, 24
Section type 3 - elements 8 to 12
Section type 4 - element 13
Section type 5 - element 14
Section type 6 - element 15
Section type 7 - element 16
Section type 8 - element 17
Section type 9 - element 18
Section type 10 - elements 19 and 20
Section type 11 - elements 21 and 22
Section type 12 - element 25

Figure 2- Finite element mesh for the footbridge.

4. VERIFICATION OF THE FOOTBRIDGE FOR STATIC LOAD

The footbridge verification was made, for a crowd static load of 5 kN/m^2, besides the structure's dead load according to NBR 7188 Brazilian's Code (1984). Two types of loading were considered in the analysis:

- Load applied in the whole length of the footbridge, in order to calculate peak load stresses acting in the supports;
- Load applied only in the central span, which allows one to calculate peak values of displacements and moments in the central span.

To calculate resulting stresses (in both load cases), a Software, SAP90 was used, admitting that the footbridge is a plane frame discretized in finite elements, according to Figure 2.

Table 4 presents the design's most critical results, when only the dead load of the footbridge and a 5 kN/m^2 overload are applied for both load cases. This table shows the values of acting and resisting moments, and also the admissible displacement for the footbridge according to NBR 8800 Code. According to this code, the relation between acting and resisting moments should have a value greater than 1. As can be observed in Table 4, this condition is satisfied, once those moments acting in the footbridge have values that are inferior to resisting moments. Displacement, even though presents a very high value, is still inferior to the admissible value.

Table 4- Conventional design – Load applied only in the central span.

	Dead load	Overload (5 kN/m^2)	Total	Admissible value
Displacement (cm)	1.00	9.50	10.50	10.80
Mom. in the middle of central span (kN-m)$^{(1)}$	41.21	262.50	303.71	-----
Mom. in the support (kN-m)$^{(2)}$	70.00	437.00	507.00	-----
Resist Mom. in the middle of central span (kN-m)$^{(1)}$	-----	-----	600.63	-----
Resist Mom. in the support (kN-m)$^{(2)}$	-----	-----	980.97	-----

(1) Load applied only in the central span of the footbridge.

(2) Load applied in the whole length of the footbridge.

5. VERIFICATION OF THE FOOTBRIDGE FOR DYNAMIC LOAD

A Software developed by Magluta (1993) was used to calculate natural frequencies, internal stresses and dynamic displacements of the structure, both in frequency and in time. This program allows the design of a vibration absorption system, in case of excessive vibrations. Natural frequencies and modal masses of the structure were obtained using this program; damping rates were adopted based in the authors' experience with similar structures. These values are showed in Table 5.

Table 5- Natural frequencies, modal mass and damping rate of first, second and third modes.

	Frequency (Hz)	Modal Mass (x 10^3 kg)	ξ (%)
1o. Mode	4.42	1.3	1.53
2o. Mode	12.16	1.5	0.93
3o. Mode	21.75	1.5	0.57

Correlating the results obtained in terms of natural frequency for the footbridge (Table 5), with the excitation frequency ranges normally adopted for walking activity (1st harmonic: f_1= 1.60 to 2.00 Hz and a_1= 0.34; 2nd harmonic: f2= 3.20 to 4.00 Hz and a_2= 0.11; 3rd harmonic: f_3= 4.80 to 6.00 Hz and a_3= 0.11) obtained by Alves et al (1999) in a previous work, one can verify that the natural frequency associated to the first mode of vibration lays in the frequency range associated to the second harmonic of human loading due to walking. The other vibration modes present natural frequencies in a frequency range higher than the one for this activity. Therefore, an amplification of the dynamic response of the structure is expected, even if the Fourier coefficient associated to the second harmonic of loading has small amplitude.

To calculate the structure's stresses when a dynamic load is applied, Fourier coefficients added of twice their standard deviation value are used. These values were experimentally obtained in a rigid platform, as described by Alves (1997). Peak values of displacement and actuating moments in the footbridge structure were then obtained.

Fourier coefficients values were calculated from a signal normalized in relation to the individual's weight and, to obtain the real loading. The adopted coefficients must be multiplied by the person's typical weight (0.70 kN). Therefore, the adopted coefficients for calculations are: a_1= 0.48 kN, a_2= 0.15 kN and a_3= 0.15 kN.

To represent the dynamic load, it was considered that 2 individuals, were walking side by side in the footbridge, at each meter length. To facilitate numerical modeling, it was considered that people walk with a 1m length pace and completely in phase, and that the dynamic load can be modeled as a punctual load applied in the adopted model's nodes. The same loading cases considered previously, for static load, were used in the dynamic modeling and results obtained are presented in Table 6. One can observe that maximum stresses obtained are associated to the second load case (platform completely loaded). This is due to the fact of considering everybody in phase associated to the first mode of vibration.

Table 6- Design for dynamic load – Original structure.

	Dead Load	Dynamic load	Total	Admissible value
Displacement (cm)	1.00	20.60	21.60	10.80
Mom. in the middle of central span (kN-m)(1)	41.21	612.10	653.31	-----
Mom. in the support (kN-m)(2)	70.00	845.80	915.63	-----
Resist Mom. in the middle of central span (kN-m)(1)	-----	-----	660.63	-----
Resist Mom. in the support (kN-m)(2)	-----	-----	980.97	-----

(1) Load applied only in the central span of the footbridge.

(2) Load applied in the whole length of the footbridge.

In Table 6 one can observe that the obtained moments (dead load of structure + dynamic load), present values that are still lower than the resistant moments, even though they are superior to those calculated by means of code's static load. Maximum total displacement presents a value that is twice the admissible value, therefore, this design does not attend NB-14 Brazilian's Design Code (1986). It should be emphasized that values in Table 6 are associated to situations where the second harmonic of the load is in resonance with the structure, and that everyone in the footbridge walks in phase. These considerations may be regarded as conservative, mainly if considered that crowd loads present a reduction, according to what is presented by (Ebrahimpour & Sacks, 1992) and (Ebrahimpour & Fitts, 1996). These reductions are associated to the fact that groups of individuals can not perform an activity with perfect synchronism as used in the verification, but more research is needed in order to consider levels of reduction presented in technical review, basically because these research works were guided for jumping activities. Something that must also be pointed out is that loads generated by human activities present reductions due to the structure-individual interaction as seen in works at the Structure's Laboratory by Alves (1997), in tests performed in a flexible structure, where smaller amplitudes were obtained for the harmonics of loading due to people. This consideration needs further research to be used safely in structure's design.

6. DESIGN OF A VIBRATION ABSORTION SYSTEM

Due to excessive displacements presented by the footbridge when a dynamic load was introduced, there was a need of designing a passive vibration absorber as described by CEB (1991), Rainer et al (1988) and Rodríguez (1996). This absorber is a mass-spring-damper installed in the middle of the central span of the footbridge. In this system, an auxiliary mass of m_{abs}= 64 kg was used, that represents approximately 5% of the modal mass associated to the structure's first mode. To calibrate the absorption system (natural frequency and damping rate), a computational system designed by Magluta (1993) was used. This system searches an optimum calibration using an optimization algorithm to reduce displacement. A reduction of 79.5% in total displacements was achieved.

Results obtained when an absorption system is added to the structure are shown in Table 7.

Table 7- Design for dynamic load – Structure with an absorber.

	Dead load	Absorber's weight	Dynamic load	Total	Admissible Value
Displacement (cm)	1.00	0.07	4.29	5.36	10.80
Mom. in the middle of central span (kN-m)(1)	41.21	3.10	121.5	165.81	-----
Mom. in the support (kN-m)(2)	70.00	2.70	177.60	250.30	-----
Resist Mom. in the middle of central span (kN-m)(1)	-----	-----	-----	660.63	-----
Resist Mom. in the support (kN-m)(2)	-----	-----	-----	980.97	-----

(1) Load applied only in the central span of the footbridge.

(2) Load applied in the whole length of the footbridge.

Through results in Table 7, it can be noticed that with an absorption system of merely 5% of modal mass, inferior actuating stresses can be obtained, increasing structural safety and reducing displacement levels. This will certainly bring more comfort for the pedestrians that use the footbridge. It must be pointed that in this analysis, fatigue serviceability verification was not considered and this may certainly increase the useful life of this type of structure.

7. VERIFICATION OF THE FOOTBRIDGE USING HUMAN COMFORT CRITERION

For verifying comfort levels when the footbridge is used, Wiss & Parmelee (1974) criterion was used. This criterion defines a factor, *R*, that is function of the structure's characteristics, defined by Eq. (1):

$$R = 5.08\left(FA \big/ D^{0.217}\right)^{0.265} \tag{1}$$

Where, *R* is Wiss and Parmelee factor; *F* is the structure's natural frequency (Hz); *A* is the maximum displacement of the structure (m); *D* is the damping of the structure (%).

R value can not exceed the admissible value $R_o = 3$, once this value is exceeded, vibrations produced in the footbridge will cause discomfort for users.

The level of vibration verification and acceptability for human comfort was conducted for two cases: (i) structure submitted to human loading; (ii) structure with an absorption system submitted to human loading. Obtained values are shown in Table 8.

Table 8- Obtained results according to Wiss & Parmelee (1974) Criterion.

	Parameter *R* value
Structure submitted to dynamic load	≈ 5.0
Structure + vibration absorption system, submitted to dynamic load	≈ 3.0

From results shown in Table 8, it can be observed that when the structure is submitted to dynamic loading due to people walking, high levels of discomfort are expected. When an absorption system is installed, *R*'s value is closer to the acceptable comfort level.

8. CONCLUSIONS

Brazilian structural design codes still do not prescribe verifications for dynamic loads due to human activities and only a few international codes and recommendations present verifications when these types of loads are acting on the structure, in terms of human comfort and some of them define minimum natural frequencies for the structure, according to the place where the activity will be conducted. However, as verified in the results presented here, it is very important to conduct an analysis considering dynamic loads due to people, once the real values that are occurring are higher than those obtained by means of a static analysis and may cause structure’s collapse or human discomfort.

9. TECHNICAL REVIEW

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