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Non destructive testing – Dynamic loading tests on large structures – Testing method

Brazilian standard for dynamic loading tests on large structures through the measurement of natural vibrations, without artificially inducing vibrations

Key words: Non destructive testing, dynamic loading, vibrations.

13 pages

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1 Scope

1.1 This standard establishes the procedure for carrying out dynamic loading testing on large structures. It addresses: scope, methodology, vibration measurements, vibration data processing, structural damage classification, mathematical modelling, model calibration and interpretation of the results.

1.2 This standard establishes minimum requirements that the methodology should accomplish for dynamic loading tests on large structures by means of natural (without artificially inducing) vibrations.

2 Definitions

The following terms are defined:

2.1 Stationary signal: A signal is said to be stationary if one calculates the average value and the standard deviation at time t_1 of the signal and the same values are obtained at time t_2.

2.2 Random signal: A random signal is the one presenting random amplitude values.

3 Background

The assumptions in this dynamic loading test type have similitude and differences in relation to the dynamic pile loading tests. Table 1 compares main characteristics.

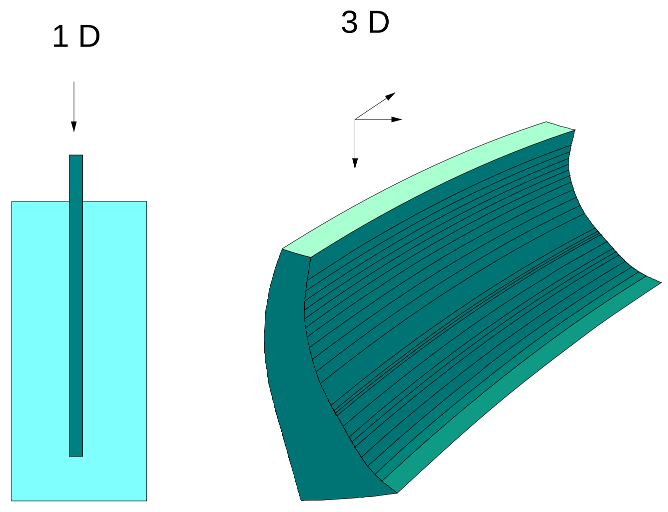

Figure 1 – Similitude between 1D dynamic pile testing and 3D large structural testing

Table 1 – Comparison between pile and large structural dynamic loading tests

Characteristics	Pile dynamic test	Dynamic test on a large dam
Dimensions	1 D	3 D
Source of vibrations	Pile hammer induces large impact	Ambient vibrations due to wind, waves, traffic, machinery or external actions
Mathematical model	1 D	3 D
Results	Pile capacity and settlement behaviour	Overall integrity assessment, damage identification, state of degradation and useful life, behaviour under new loading system

4 Dynamic principia

The dynamic response is given by the following formula, which can be found in any structural dynamics textbook:

$$x_r = F_r \left(\frac{K_r^{-1}}{1 - \frac{f^2}{f_r^2} + i\,2\zeta_r \left(\frac{f}{f_r} \right)} \right) \qquad (1)$$

Where:

x_r displacements or structural response;

F_r applied forces;

K_r structure stiffness, i.e., spring constant opposing the direction of movement;

f frequency;

f_r resonance frequency;

ζ_r damping coefficient;

i is the imaginary number ($i = \sqrt{-1}$)

In the previous equation sub r's refer to a mode shape in which there is response amplification due to a phenomenon called *resonance*, which is larger or smaller in relation to the amplitude of structural response in a particular frequency. The damping parameter gives the rate of energy loss through friction between structural elements, or in small (micro) cracks surfaces.

4.1 Static behaviour

Putting $f = 0$ in equation (1), one gets:

$$x(0) = \frac{F(0)}{K(0)} \qquad (2)$$

This formula shows that the static response is obtained as a product of the applied force by the stiffness inverse, showing that the elastic domain can be considered as a sub-set of the dynamic domain.

4.2 Dynamic behaviour at the resonance frequency

Putting $f = f_r$ in equation (1), one gets:

$$x_r = \frac{F_r}{2K_r \, \xi_r \; i} \qquad (3)$$

This equation shows an amplified response for mode shape r. The amplification factor is 1/(2ζ) in relation t the static response.

4.3 Behaviour of a simple undamped system

It is possible to show that in a simple undamped mass-spring system, the resonance frequency (f_r) is given by:

$$f_r = \sqrt{\frac{K_r}{m_r}} \qquad (4)$$

Where:

K_r is the modal stiffness

m_r is the modal mass, i.e., the mass that interferes in this mode shape.

This equation appears in any textbook on dynamics and shows the relationship between frequency and structural stiffness.

5 Quantities to be measured

The dynamic loading tests require measurement of natural vibrations due to ambient excitation due to wind, waves, traffic, external actions, etc..

5.1 Measurement of natural vibrations

The measurement of natural vibrations with accelerometers is required for the dynamic loading tests, due to:

a)The use of accelerometers is relatively easy and straight forward. With a few measurement positions strategically located on the structure, it is possible to assess the whole vibration behaviour;

b) It is not necessary to force vibrations or any type of large loading;

c) Accelerometers are referenced to the gravity, therefore the baseline of the measurements is always obtained as the acceleration of gravity is a known value;

5.2 Instrumentation

Figure 2 presents the instrumentation needed. It consists of highly accurate accelerometers, a datalogging system and an oscilloscope.

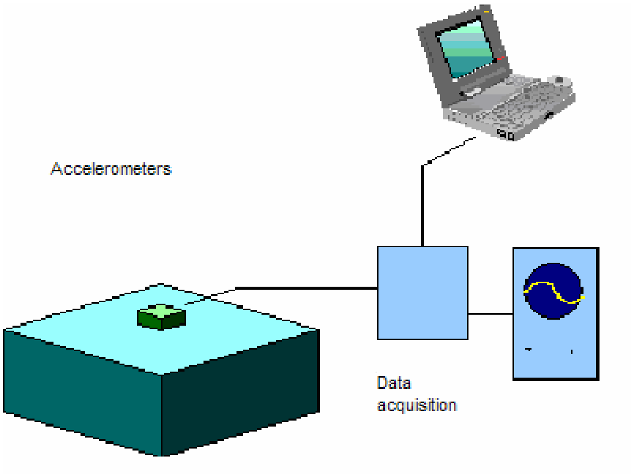

Figure 2 – example of instrumentation for measurement of vibrations

The main characteristic of the instrumentation system is the very high accuracy needed to measure very low vibrations at very low frequencies. The accelerometers should be accurate enough to measure 10^{-8} *g*, where *g* é the acceleration of gravity.

Table 2 gives the specification of the equipment needed.

Table 2 Instrumentation specs

Characteristics	Values
Accelerometer range	0 to 1 g
Sensitivity of the sensors and data acquisition system	Minimum of 10^{-8} g
Direction of vibrations	Vertical and horizontal
Data acquisition system analogue-digital conversion (A/D)	minimum 16 bits
Gain	Variable: 1, 10, 100 and 1 000 times
Low pass *anti-aliasing* filter	10 Hz
Frequency range	0 to 10 Hz
Frequency resolution	Better than 0.0001 Hz
Sampling rate	30 to 400 Hz
Digital filtering	54 dB by octave (*roll-off*)
Modal frequency separation	0.05 Hz

By using the system specified in table 2 one can assess the accuracy in terms of displacement by considering simple harmonic movement. Figure 3 shows the results of this analysis, in which for a frequency of 0.1 Hz of a structure, the accuracy of the minimum displacement that can be measured is close to the wavelength of light.

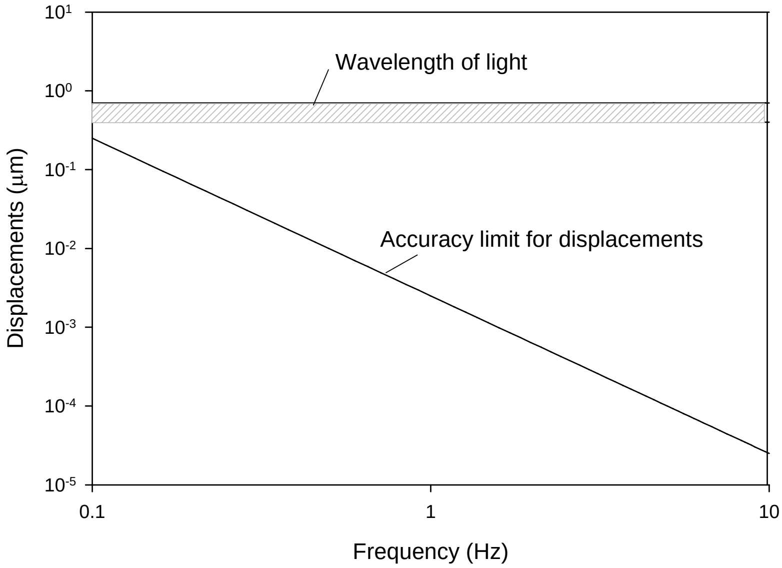

Figure 3 – Accuracy of measured displacements

6 Instrumentation plan

6.1 Necessary documentation

The following documentation is necessary to establish the measurement plan and analyse the results.

a) Drawings with all dimensions of the structure, including foundations;

b) Visual damage inspection report.

The above information is necessary for analysing and modelling the structure. If they are not available, a topographic survey and a visual inspection should be carried out to check for any type of damage, cracking, etc.

The following information is useful, although not a *sine qua non* condition:

a) Structural and foundation design report;

b) Detailed structural design

7 Measurement positions on a structure

Measurement positions on the structure are planned to maximise the quality of information for the overall structure in the least number of measurements. The selection of these locations depend of the type, shape and behaviour of the structure. Some examples follow.

7.1 Bridges

Figure 4 shows the best positions to observe a bridge deck, pillars and foundations. P1 is located on the bridge deck but always off the symmetry axis of the structure, in order to be influenced by torsion. P1 is located on the 1/3 dimensions either way. P2 and P3 aim at looking at the pillar and foundation behaviour. These measurements are oriented along the horizontal and transverse axes.

P4 is for assessing foundation behaviour, but only taken if P2 and P3 already indicated a problem.

7.2 Tall buildings and towers

For tall buildings and towers the best position is on the top, but always sideways, i.e., off the symmetry axes of the structure. The accelerometers should be oriented along transversal and longitudinal axis.

7.3 Dams

Measurements in dams take place on the dam crest, also off the symmetry lines, with accelerometers oriented along-valley and across-valley.

7.4 Roofs

The most important locations for measurements are at the unsupported side of a roof and close to their sides. Accelerometers should be oriented along the transverse and vertical axes.

8 Measurement time and amount of data

The quality of field data depends not only on the accuracy of the measurements, but on the sampling frequency and time span at each measurement location. Additionally, the spectral analysis of each time signal requires a large amount of data and also response resolution at each resonance frequency. The criterion for this is that the analysis bandwidth is less than four times the resonance bandwidth, *i.e.*, a minimum of four data points is required around each resonance peak.

In addition to the above criteria, it is necessary to obtain the average value of the statistical fluctuations caused by the random excitation. In such case, the error should not be larger than 10% and the number of measurements times the bandwidth should be larger than 100.

The minimum measurement time span (T in seconds) should be:

$$T = \frac{200}{f_r \zeta_r} \text{ (in seconds)} \qquad (5)$$

Where f_r and ζ_r are the modal frequency and damping coefficient, respectively.

In the case of slabs or decks, the fundamental frequency depends on the span and can be estimated by:

$$f_r = L^{-0.9} \qquad (6)$$

where L is the span width in metres and the modal frequency f_r in Hertz

Considering this quantity of data, the mode "*r*" will present an error which is less than 4% and its variance is less than10%, leading to an overall error less than 10.8%, which is adequate for the purpose of the analyses.

Example:

At 0.5 Hz frequency and 2% damping, the time T to collect data on a structure is:

$$T = \frac{200}{0.5 \times 0.02} = 20000\,\text{s} = 5.6\,\text{hours}$$

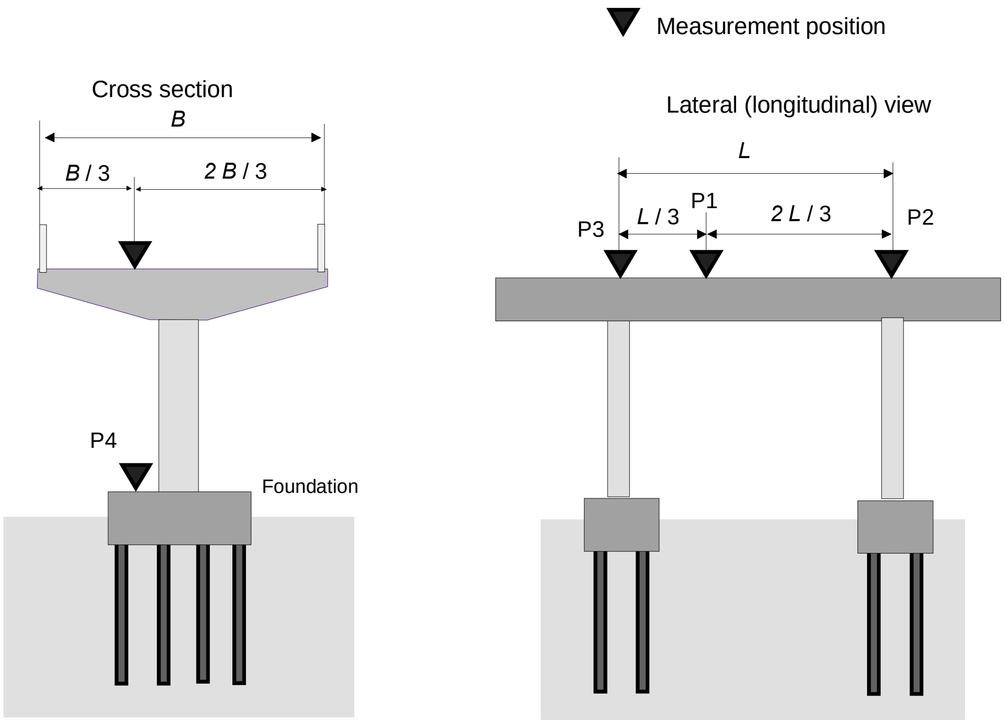

Figure 4 - Measurement locations on bridges

9 Data processing

Field data should be then processed, as described in this section by digital signal analysis techniques. Commercial software can be used, provided they are fully tested and available from reliable sources.

9.1 Spectrum analysis

The first step is spectral analysis in the frequency range of 0 to 10 Hz with a bandwidth small enough to resolve the resonance peaks. One, then, gets

a) Resonance frequencies;

b) Maximum accelerations;

c) Maximum displacements at each resonance frequency;

d) Tilt angles.

Figure 5 presents the way the spectrum analysis should be plotted. The normalised ordinates present square of acceleration amplitudes normalized against frequency in units g^2/Hz, where g is gravity. The abscissa is frequency ranging from 0 to 10 Hz. The peaks represent the structural resonances.

Figure 6(a) presents a spectrum with a fundamental frequency of 3.6 Hz and other smaller peaks. These low frequency resonances may play an important role in the analysis of the structure, as lower frequencies relate to lower stiffness. These data is replotted in figure 6(b) with a log ordinate scale to enhance low amplitude peaks.

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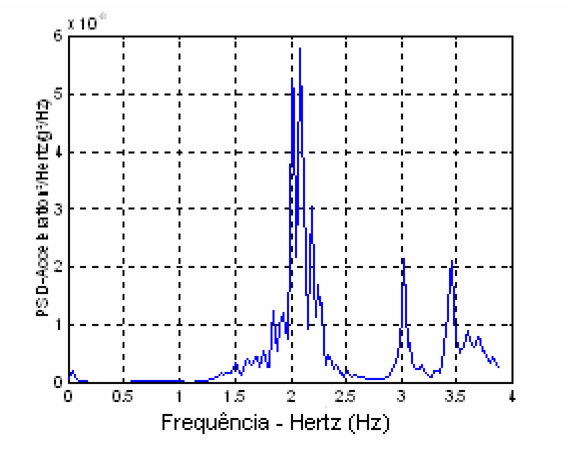

Figure 5 – Example of a spectrum of a structure

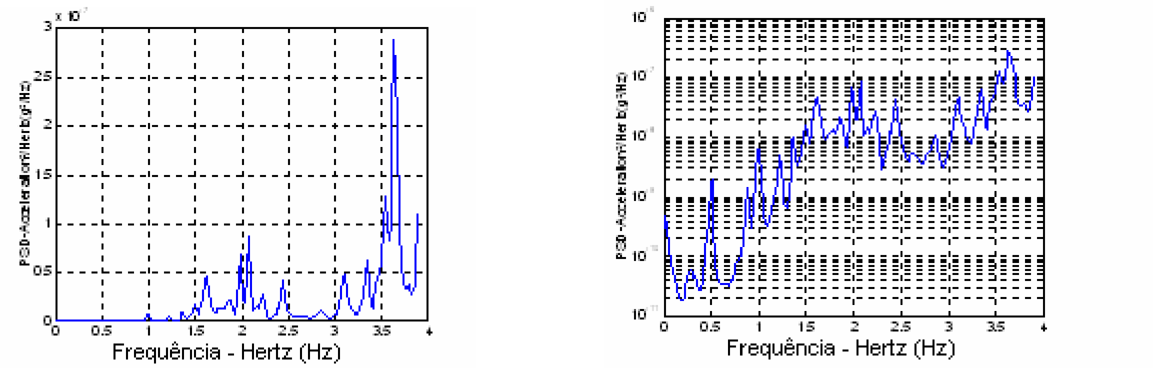

Figure 6 – Example of structural spectra with several small low frequency resonances: (a) left, arithmetic ordinate scale ; (b) log scale

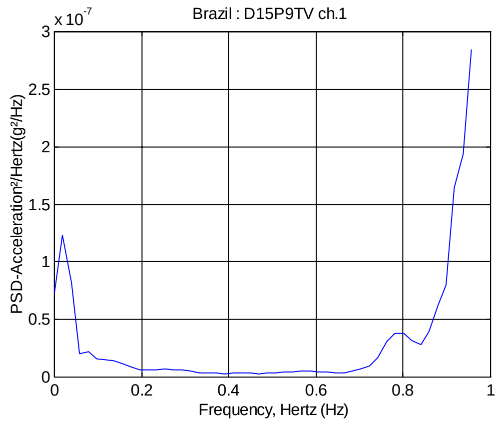

Figure 7 – Example of a structural spectrum showing very low frequency resonances at about 0.03 Hz

Figure 7 presents the results of measurements on a structure showing a very low frequency resonance at about 0.03 Hz.

10 Damping analysis

Structural damping is a very important measurement to look at the progress with time of structural damage. The technical literature listed in the references discuss the methods. The text below review some of them specifies the one in section 10.4.

10.1 Autocorrelation method

Shall not be used.

10.2 Half power bandwidth method

It is possible t estimate damping coefficient at any resonance through spectral analysis. However, like the autocorrelation method, this method yields average results, without providing a relationship between damping and amplitude. Therefore, for a well defined resonance (as in the peak at 3.05 Hz in figure 5) it is necessary to locate two points in which the response is 0.707 the peak value.

The damping coefficient is then given by

$$\zeta_r = \frac{B_r}{2 f_r}$$

where B_r is the bandwidth (figure 8)

The difficulty in applying this method can be depicted from figure 5 spectrum. The fundamental frequency, taking place at 2.1 Hz, presents several very close peaks,.*i.e*, a *fragmented resonance*. This leads to a practical difficulty for applying this method, as many structures present fragmented resonance. Therefore, this method should not be used.

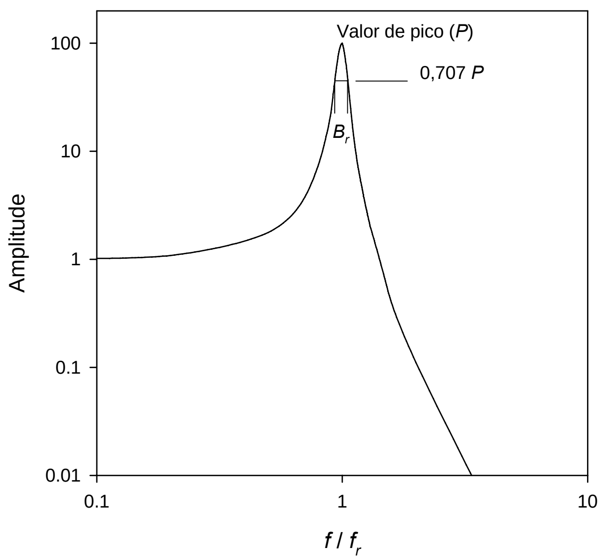

Figure 8 - Amplitude *versus* f / f_r

10.3 Induced vibrations method

It is possible to determine damping by artificially inducing vibrations, then turning off the excitation source, ou applying a large displacement and remove it, leading the structure to oscillate and to dissipate energy. If one plots oscillations versus time, it is possible to figure out damping from the decaying oscillatory curve.

This method is difficult to apply, due to the need of applying induced vibrations or displacements, therefore, it is not recommended.

10.4 Random decrement (*Randec*) method

The Randec method is recommended by this standard. It outputs a relationship between damping and amplitude (figure 9). All structures, irrespectively of its materials, present such damping versus amplitude curve, with the following characteristics (figure 10): (a) a low amplitude plateau; (b) a transition slope; (c) a high amplitude plateau.

For the application of the Randec method, the following requirements prevail:

a) Measured signals should present stationary and random data. It is important to test the signals for these requirements through statistical analyses.

b) The amplitude window cannot supersede other windows.

c) The amplitude window cannot exceed 5% of the total range;

d) Individual pairs of damping / amplitude values, have to be averaged from at least n =1000 measured datapoints.

e) If n < 100, the corresponding datapoints should be rejected.

Figure 9 shows typical results from Randec analysis that should be provided by every structure subjected to dynamic loading test.

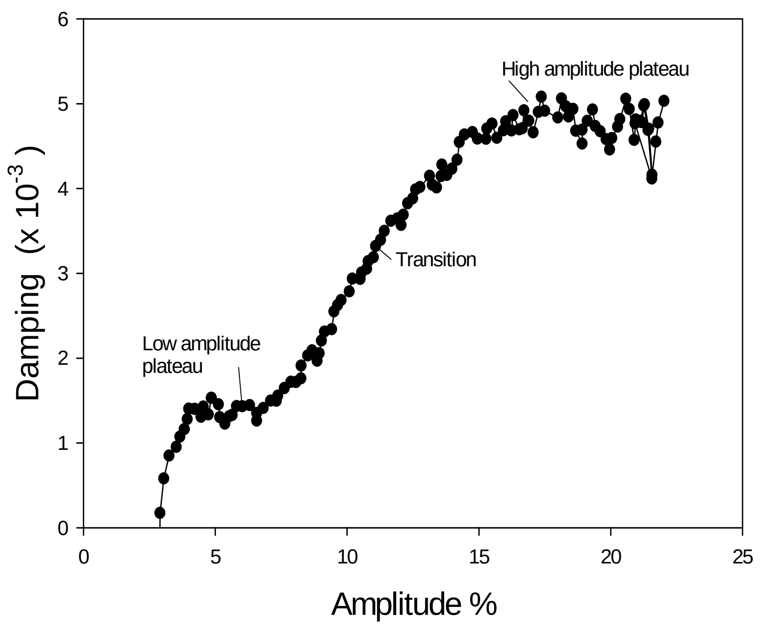

Figure 9 - Damping versus amplitude of a structure

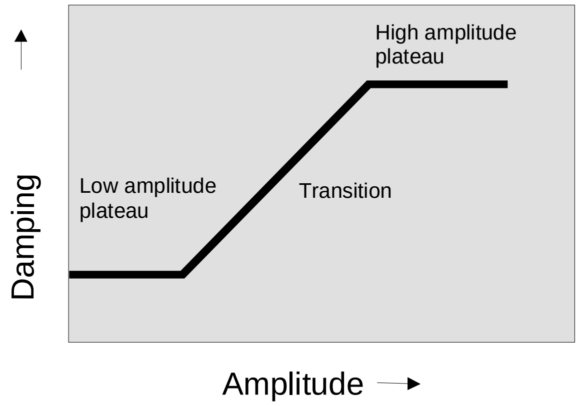

Figure 10 - Simplified representation of the damping versus amplitude curve

The purpose of obtaining a damping curve from a set of measurements on a structure is twofold: first, to enable numerical extrapolation of the structural behaviour from the low to high amplitude response; second, to enable the assessment of aging, by comparing different sets of measurements along time.

The numerical extrapolation should take into account the non-linear damping relationship with amplitude. Many cases exist where a 3% change in the spectrum, corresponds to a much larger change in the damping curve. Therefore, modelling of large responses can rely on the Randec method for reliable source of non-linear damping values.

The damping curve change its shape is directly related to damage progress. Cracking, chemical change and other aging aspects affect damping. Therefore, once one obtains a baseline, the follow up of structural aging is possible by additional measurements.

11 Numerical modelling

The next step of the analyses is to build a numerical model of the structure through a dynamics structural analysis computer program and to obtain the frequency eigenvalues, each corresponding to a modal shape.

The steps are:

a) Enter 3D dimensions of the structure obtained from original drawings or structure survey;

b) Enter original or undamaged material properties, such as Young's modulus, Poisson's ratio and damping values for all structural elements;

c) Run the program and obtain eigenvalues or resonance frequencies for each mode shape;

The model is then calibrated against the measured spectra by a trial and error method in which the material properties are changed and the resulting eigenvalue frequencies are obtained, until there is an agreement between the calculated and measured frequencies at least in the first five vibration modes. When this is achieved, the model is then considered to be calibrated.

Finally the calibrated model can be used for further analyses of stresses and displacements under any loading scenario.

12 Criteria for assessing behaviour and damage

There are two important issues to be analysed. The first, relates to material behaviour, the second, to global structural behaviour and collapse. The structural behaviour has to comply to Brazilian and international standards for structures.

12.1 Vibrar rating

The vibrar rating is a empirical parameter which is very useful to analyse the damage levels of all structures. It was originally developed by Koch (1953) based on a large database relating structural damage level with other parameters. The vibrar rating V is given by:

$$V = 10 \log (160\, \pi^4 A^2 f^3) \qquad (5)$$

where:

A is the amplitude of vibrations in centimetres (cm);

f is the frequency in Hertz (Hz).

V should be calculated for each measuring location and every accelerometer direction either from the measurements and also from the numerical model for different loading scenarios.

Table 3 gives the relationship between *V* and damage level.

Table 3 - Damage level and vibrar rating

V	Damage level
10 - 30	None
30 - 40	Light damage
40 - 50	Severe damage
50 - 60	Collapse

12.2 Final use of the model

The calibrated model should be used for analysing structural response under all possible loading scenarios.

13 Final report

The final report should present:

a) The purpose of the dynamic loading test;

b) A description of the structure and its state;

c) Drawings with dimensions;

d) Location of the measurements and their directions, by the letters vertical)*V*), transversal *(T*) and longitudinal (*L*);

e) Characteristics of the instrumentation equipment, comparing with data in table 2;

f) Measured spectra;

g) Damping curves versus amplitude;

h) A description of the mathematical model and the computer program used;

i) Characteristics of the mathematical model;

j) Resulting mode shapes and frequencies;

k) Results from the numerical analyses: stresses and displacements for various loading scenarios;

l) A table comparing measured and calculated frequencies for undamaged structure and calibrated model;

m) A table showing vibrar ratings for each measured position and direction comparing measured and calculated values for different loading scenarios;

n) Conclusions;

o) Recommendations.

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