SDSS'Rio 2010 STABILITY AND DUCTILITY OF STEEL STRUCTURES
E. Batista, P. Vellasco, L. de Lima (Eds.)
Rio de Janeiro, Brazil, September 8 - 10, 2010

INFLUENCE OF SYSTEM UNCERTAINTIES ON STRUCTURAL DAMAGE IDENTIFICATION THROUGH AMBIENT VIBRATIONS OF STEEL STRUCTURES

Leandro Fadel Miguel*, Letícia Fadel Miguel*, Jorge D. Riera*, Marta G. Amani and Raúl O. Curadelli****

*Federal University of Rio Grande do Sul, Porto Alegre, Brazil
e-mails: leandro.miguel@ufrgs.br, letffm@ufrgs.br, jorge.riera@ufrgs.br

** Universidad Nacional de Cuyo, Mendoza, Argentina
e-mail: amanimg@yahoo.com, ocuradelli@yahoo.com

Keywords: Identification, Damage Detection, Structural Monitoring, Ambient Vibrations.

Abstract*. The practical difficulties presented by forced vibration testing of large steel structures, such as tall buildings, transmission lines or bridges, led to an increased interest in structural monitoring through ambient vibrations, which usually allows the proper identification of modal properties, natural frequencies, damping and modes of vibration. Changes in these modal properties constitute an indication of structural damage, which may then be assessed on the basis of experimental evidence. The authors proposed an approach to determine the so-called damage damping and stiffness matrices, which are essential to identify the location and intensity of damage. No restrictions were introduced on the damping matrix of the system. The approach requires ambient vibration data of all relevant coordinates used in the structural model, which are processed employing the SSI method. In practice, the identification method is seriously hampered by ambient factors such as temperature or humidity. In general those effects must be filtered out in other to obtain a reliable diagnosis of damage, approach that demands long term monitoring. In this paper, an alternative approach is explored, based on the introduction of error damping and stiffness matrices. Data on both matrices is generated on the basis of observed variations of structural member stiffness and damping caused by ambient factors. The influence of this uncertainty on the identified spectral properties is assessed by simulation.*

1 INTRODUCTION

In recent contributions the authors examined experimental evidence concerning the influence of ambient factors on the spectral properties of dynamic systems [1], [2], [3]. Proposed procedures to eliminate those effects from vibration measurements aimed at damage detection in structural systems [4] demand extensive monitoring to cover the range of expected variations of ambient conditions. These requirements may render them either too expensive or simply unfeasible due to technical or logistic reasons. Moreover, the issue introduced by noise in the system matrices, which should be distinguished from noise in the vibration recording system, is largely ignored. Empirical or semi-empirical results of those contributions are briefly described for completeness in next section.

In this paper, however, the authors follow an entirely different approach. Changes in the system matrices are assumed to belong in one of two types: *reversible and irreversible*. The first are due to so-called ambient factors, which include temperature, humidity, and other effects, while the second constitute evidence of *damage*. In the absence of damage, which is the topic of the present study, the components of the mass, damping and stiffness matrices of the system *must necessarily be stationary random processes*. It follows that the components of the error matrices, defined as the difference between the system matrices at any arbitrary time and the reference matrices that describe the condition of the system in its initial state must be random variables with zero mean. Hence, the effect of the so-called *error matrices* on the system spectral properties is assessed first. These matrices are generated by multiplying all components of the reference matrices by uncorrelated normally distributed random coefficients with zero mean and prescribed standard deviation.

2 INFLUENCE OF AMBIENT FACTORS ON SPECTRAL PROPERTIES OF STRUCTURAL SYSTEMS

In previous papers [5], the authors examine available experimental evidence on the influence of ambient factors on steel and concrete structures. In [1] it was shown that, in a limited number of samples of concrete structures, the *expected value* η of the ratio between observed natural frequencies of structural systems at a mean temperature different from the reference temperature and the frequencies measured at the reference temperature may be estimated by the equation:

$$\eta = 1 - 0{,}002\, \Delta T - 0{,}0003\, \Delta h \quad (1)$$

In which ΔT denotes the temperature difference (positive value indicates temperature increase) and Δh the change in atmospheric humidity. Similarly, the expected value ξ of the ratio between the critical damping ratio affected by ambient factors and the damping ratio measured at reference conditions is given by:

$$\xi = 1 + 0{,}018\, \Delta T - 0{,}0049\, \Delta h \quad (2)$$

On the other hand, the following expression was obtained for steel structures [3]:

$$\eta = 1 - 0{,}00051\, \Delta T \quad (3)$$

By means of simple models of struts, Riera et al (2008) estimate that the maximum values for the temperature coefficients in Eq. (1) span between 0.005 (elements subjected to tensile force) and 0.015 (compressed elements). In case of steel structures (Eq. 3) these limits are 0.0084 and 0.0028, respectively.

In the same study, in order to assess the influence of temperature on natural frequencies, an artificial neural networks was constructed and it perform in the same way: the network input is a ΔT value which means changes in temperature (˚C) from reference values (increase is positive) and the output provides a correction factor that should be multiplied by the measured natural frequency. The linear regression equation (Eq. 3) and results obtained with the ANN for the training and validating subsets are shown in Figure 1.

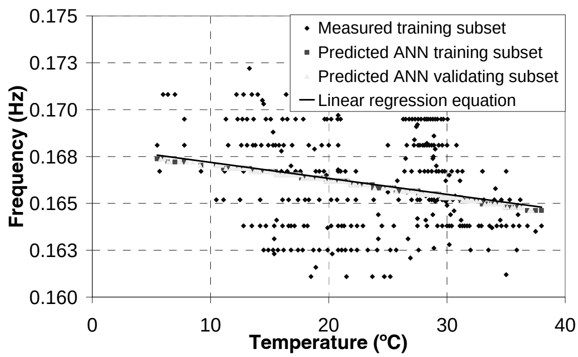

Figure 1: Linear regression equation and ANN results.

If the equation for the frequency change is thus of the form:

$$\eta = 1 - c\,\Delta T \tag{4}$$

It may be expected that the stiffness affected by ambient factors and the reference stiffness will be related by $\eta^{1/2}$. If this ratio is denoted as β, then it follows that:

$$\beta = 1 - \tfrac{1}{2}\, c\,\Delta T \tag{5}$$

Consequently, Eq.(5) estimates the expected value of the ratio between stiffness coefficients in the structure affected by ambient factors and stiffness coefficients in the structure in the reference condition, in which the spectral properties were experimentally determined. Note that ΔT denotes the mean temperature change between both conditions, while the temperature as well as the slenderness and axial loads in individual members vary throughout the structure. In this context, it is proposed herein that the ratio between corresponding stiffness coefficients K_{ij} is a random variable β_{ij} with mean given by Eq. (5) and variance to be later defined. In the simulation analysis, the stiffness matrix affected by ambient factors is obtained by multiplying the coefficients K_{ij} of the reference matrix by a set of uncorrelated random numbers β_{ij}.

On the other hand, if C_r and M_r are the generalized damping and stiffness coefficients of the r^{th} mode the structure, then under certain conditions and proportional viscous damping the following equation holds:

$$Cr / Mr = 2\,\zeta r\,\omega r \tag{6}$$

In which ζ_r and ω_r denote the critical damping ratio and the frequency of mode r. A similar equation may be written for the matrix of the system affected by ambient factors. Assuming that the mass matrix remains constant, the mean ratio γ between the coefficients of the modified and reference damping matrices can be shown to be of the form:

$$Cr / Cro = (\zeta r / \zeta ro)\,(\omega r / \omega ro) \tag{7}$$

The left-hand side of Eq.(7) may be identified as γ while the ratios between parenthesis in the right-hand side are ξ and η, respectively, leading to:

$$\gamma = \eta\,\xi \tag{8}$$

For concrete structures, substitution of Eqs. (2) and (4) in Eq. (7) leads to:

$$\gamma = 1 + 0.016\,\Delta T \tag{9}$$

Using the same arguments, the coefficients of the damping matrix after and before the introduction of ambient factors are related by a random variable γ_{ij} with mean given by Eq.(8).

3 INFLUENCE OF ERROR MATRICES ON SPECTRAL PROPERTIES OF STRUCTURAL SYSTEMS

3.1 Effect of changes in the stiffness matrix

Some theoretical results will be recalled first: if the stiffness matrix of a linear system without damping is multiplied by a constant factor, the eigenvectors, i.e. the vibration modes, do not change, but the natural frequencies should be multiplied by the square root of the factor. This would be equivalent to considering an error stiffness matrix that is proportional to the original matrix.

The influence on the mean spectral properties introduced by stationary random changes in the stiffness matrix due to ambient factors will be assessed first by simulation, considering for such purpose the typical steel truss structure shown in Figure 2. This plane Warren truss consists of 37 nodes and 71 steel bars, which have a cross section of 2×10^{-3}m^2. Young's modulus of the material is 2×10^{11}N/m^2 and its mass density 7.86×103kg/m^3. The height of the truss is 9m while the total length is 168m. The supports of the structure are modeled as two hinged supports at nodes 1 and 37 and as a roller support at node 19. The pinned end allows nodes to rotate freely with all three translations restricted.

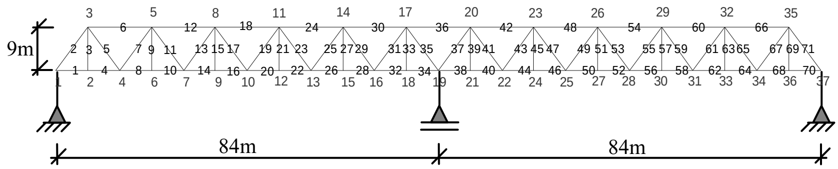

Figure 2: Continuous Warren truss adopted for simulation study.

Stiffness matrices affected by noise were generated by multiplying all components of the reference stiffness matrix by uncorrelated normally distributed random coefficients with zero mean and coefficients of variation (CV) equal to 0.01, 0.03, 0.05 and 0.10. For each CV, 100 disturbed simulated stiffness matrices were generated. The natural frequencies for the first seven modes were next determined for each simulated sample and the corresponding mean calculated next (Table 1).

Table 1: Natural frequencies comparison (Hz).

Original	*CV = 0.01*		*CV = 0.03*		*CV = 0.05*		*CV = 0.10*	
	Mean	Difference (%)	Mean	Difference (%)	Mean	Difference (%)	Mean	Difference (%)
3.14377	3.1440	-0.01	3.1419	0.06	3.1388	0.16	3.1243	0.62
4.74475	4.7449	0.00	4.7417	0.07	4.7373	0.16	4.7151	0.62
8.63623	8.6357	0.01	8.6292	0.08	8.6255	0.12	8.6023	0.39
11.7569	11.7573	0.00	11.7487	0.07	11.7281	0.24	11.6536	0.88
11.9576	11.9584	-0.01	11.9549	0.02	11.9476	0.08	11.9270	0.26
18.6109	18.6103	0.00	18.5934	0.09	18.5808	0.16	18.5277	0.45
20.6468	20.6454	0.01	20.6247	0.11	20.6125	0.17	20.5373	0.53

It may be seen that a trend to observe *smaller* frequencies that steadily decrease with the coefficient of variation of the fluctuating components of the stiffness matrix is perceptible for all modes, approaching 0.5% for a CV of around 10%. *Since frequency changes of this order would already be indicative of damage, it is clear that the effect cannot be disregarded* and that further studies are needed, first to quantify it in different structural systems and then to filter it out in damage identification procedures.

3.2 Influence of changes in the damping matrix

Changes in damping can be quite relevant in the detection of damage in structural systems [2]. Thus, the influence of ambient factors on critical damping ratios, introduced by random changes in the damping matrix, will be assessed by means of numerical simulation. For this purpose, the three bays 10-stories high steel frame shown in Figure 3, considered earlier [6], was studied. The structure was designed in accordance with the provisions of the Uniform Building Code. The total mass per floor is 47 t and damping matrix is assumed to be proportional to a combination of the mass and the stiffness matrices (Rayleigh damping). The modal damping ratio in each mode is shown in Table 2. Frame and member dimensions are also indicated in Figure 3.

The noisy damping matrices were generated by multiplying all components of the original damping matrix by uncorrelated normally distributed random coefficients with zero mean and coefficients of variation (CV) equal to 0.1 and 0.15. These values were adopted because for CVs lower than about 0.15, the damping matrices with random noise continue being approximately proportional, and thus, there is no difficult to obtain the modal damping ratios as in the original damping matrix. For each CV, 1000 simulated noisy damping matrices were generated. The modal damping ratios for the first seven modes were next determined for each simulated sample. The mean values of the modal damping ratios for each mode obtained from the simulated damping matrices affected by random noise are compared in Table 2 with the modal damping ratios for the modes of the original structure. Table 2 also presents the corresponding coefficients of variation of the population of simulated structures. *The results show slight changes in the modal damping of the first three modes, which increase with the CV of the noise terms.*

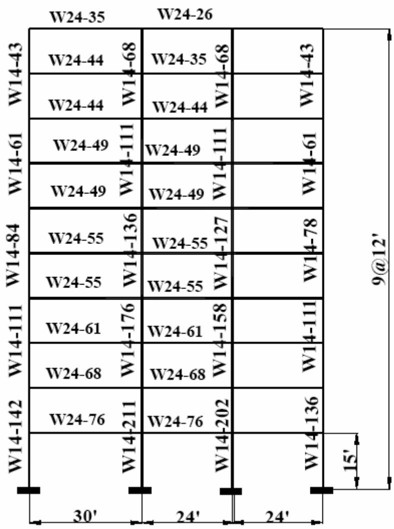

Figure 3: Three bays 10-stories high steel frame adopted in simulation study.

Table 1: Modal damping ratios comparison.

ξ_0	CV = 0.10		CV = 0.15	
	$\xi_{0.1}$	Difference (%)	$\xi_{0.15}$	Difference (%)
0.0100	0.0103	-3.28	0.0105	-4.83
0.0051	0.0056	-7.97	0.0055	-7.42
0.0049	0.0052	-6.15	0.00488	1.15
0.0056	0.0057	-1.89	0.0056	-1.45
0.0068	0.0069	-1.10	0.0069	-1.10
0.0082	0.0083	-0.84	0.0082	0.00
0.0100	0.0100	0.00	0.0100	0.00

For higher values of the CV the proportionality property of the damping matrices including noise is no longer an acceptable assumption and the assessment of the influence of noise becomes more difficult.

4 CONCLUSION

In this paper, the effect of so-called *error matrices* on the spectral properties of structural systems is examined. The study aims at providing data to assess the range of application and general validity of empirical expression obtained earlier by the authors. The error matrices were generated herein by multiplying all components of the reference matrices by uncorrelated normally distributed random coefficients with zero mean and prescribed standard deviation.

The influence on the natural frequencies due to random changes in the stiffness matrix due, for instance, to ambient factors, was assessed first, considering for such purpose a typical steel Warren truss. A trend to lower frequencies that steadily decrease with the CV of the fluctuating components of the stiffness matrix is perceptible for all modes, approaching 0.5% for a CV of around 10%. Since frequency changes of this order would already be indicative of damage, it is clear that the effect cannot continue being disregarded in efforts to detect and quantify damage through ambient vibrations.

The influence of ambient factors introduced by random changes in the damping matrix was assessed in a three bays 10-stories high steel frame. Slight changes in the modal damping of the first modes, which increase with the CV of the noise terms were detected.

These results are considered as an intial step in efforts to reduce uncertainties in procedures proposed to detect and quantify damage in steel structures through ambient vibration monitoring.

REFERENCES

[1] Amani, M.G., Curadelli, R.O., Riera, J.D., Ambrosini, R.D. “Influencia de Factores Ambientales en las Propiedades Espectrales de Estructuras de Hormigón”. *XXXIII Jornadas Sudamericanas de Ingeniería Estructural*, Santiago, Chile, 2008.

[2] Curadelli, R.O., Riera, J.D., Ambrosini, R.D., Amani, M.G. “Damage detection by means of structural damage identification”. *Engineering Structures*, 30, 3497-3504, 2008

[3] Fadel Miguel, L.F., Riera, J.D., Miguel, L.F.F. “Influência de Fatores Ambientais nas Propriedades Espectrais de Estruturas Metálicas”. *XXXIII Jornadas Sudamericanas de Ingeniería Estructural*, Santiago, Chile, 2008.

[4] Alampalli, S. “Effects of Testing, Analysis, Damage and Environment on Modal Parameters”. *Mechanical Systems And Signal Processing*, 14(1), 63-74, 2000.

[5] Amani, M.G., Riera, J.D., Curadelli, R.O. “Procedures for Structural Damage Identification through Ambient Vibrations”. *Proceedings of 4th World Conference on Structural Control and Monitoring*, San Diego, CA, USA, 2006.

[6] Bertero V, Mahin S, Herrera R. “A seismic design implications of near-fault San Fernando earthquake records”. *Earthquake Engineering and Structural Dynamics*, 6, 31–42. 1978.