LOCAL MODES OF VIBRATIONS FOR CIVIL STRUCTURAL HEALTH MONITORING

G.Z. Qi[2], X. Guo[4], P. Chang[1], X. Qi[4] and W. Dong[3]

[1] *Department of Civil Engineering, University of Maryland/College Park, USA*
[2] *InfraTech, Inc. Silver Spring, Maryland, USA*
[3] *Risk Management Solution, San Francisco, California, USA*
[4] *Instutute of Engineering Mechanics, CEA, Harbin, China*

ABSTRACT :
The technologies of the non-destructive structural health monitoring (SHM) can be classified into three categories: (1) imaging and wave scanning, (2) vibration-based technology and (3) fatigue residual life estimation. This paper limits the discussion to the vibration-based SHM. In recent decade SHM using vibration-based technology is going along three directions: (1) dense-measurement on structures/bridges on site or laboratories to make the measurements near by the locations where the damages may occur, (2) improved sensing technology for more effective data collection, networking and data transfer and (3) methodologies to analyze the data in order to extract the signals to characterize the health status of structures. All these works could make sense on SHM as long as the signal to characterize the localized damage was included in the data observed in the structures. This paper discusses how to ensure such signal can be observed in a structure. The new findings of the research show that in order to successfully monitor the health status of a structure it is necessary to make the local modes measurement.

KEYWORDS:
Structural health monitoring, Infrastructure, Local modes of vibration, Local measurement, Global modes, Local modes excitation.

1. INTRODUCTION

Structural health monitoring may be used to measure damage in a structure, and possibly obtain a prognosis of the long-term health of the structure. It is, therefore, a powerful engineering tool in life-cycle management of the structure. Aging infrastructure is a severe problem in the United States. For example, the collapse of the Interstate 35W bridge in Minnesota on August 1 in 2007 caused 13 deaths and significant economic losses. More than half of the 690,000 bridges in US are more than 50 years old. Similar problems exist in other infrastructures, such as rail, power distribution network, and pipelines. SHM is especially importance after major events, such as earthquakes or man-made disasters, to determine if the structure can be used for its designed purpose, or does it require retrofitting and/or replacement.

Broadly speaking, the technologies of the non-destructive structural health monitoring can be classified into three categories: (1) Imaging and wave scanning by using ultrasound, X-ray, acoustics or electromagnetic wave; (2) Vibration- based technology and (3) Fatigue residual life estimation based on the S-N curves. We here limit the discussion about SHM to the vibration-based one only. The major difficulty of structural health monitoring results from the fact that the damages occurring in structures, especially at earlier stages, are localized. Consequently, recent works on SHM in vibration-based technology have followed three directions: (1) dense-measurement on structures/bridges on site or laboratories to make the measurements near by the locations where the local damages may occur (Shinozuka, et al, 2004, Gao, et al. 2001, Isoda et al, 2001), (2) improved sensing technology for more effective data collection and data transfer (N. Xue et al, 2004, G. Park et al, 2000) and (3) methodologies to analyze the data in order to extract the signals to characterize the health status of structures (M. Tong et al, 2005, Pei and Chang, 2003, Gao and Spencer 2002, Fritizen and Bohlr 2001,Lian and Lee 2001, Vecchio and Auweraer 2001, Loh and Chien 2001 Shinozuka et al, 2000, Hou et al, 2000). All these works make sense on SHM as long as the signal to characterize the localized damage was included in the data observed in the structures. This paper discusses how to ensure such signal can be observed in a structure. The new findings from this research show in order to successful monitor the health status of a structure it is necessary to make the local modes measurement.

2. LOCAL MODES MEASUREMENT

2.1 The local modes measurement

This is a follow-up of the paper published in the journal of Earthquake Engineering and Engineering Vibration (Qi et al, 2005), in which "local measurement" was defined. However, the local measurement may cause in confusion with some understandings in the measurement. One is the dense sensing measurement being taken in places of a structure near by the locations where the damages may occur; the other is the measurement of strains in a structure, which may be treated as the local measurements due to their differentiation nature of the displacements along spaces. Local modes mean the vibration of a member in a structure, which represents the vibration nature of the member itself only. The local modes are distinguished from the global ones, in which the members' vibrations along with the entire structure are included correspondingly.

2.2 Necessity in Making Local Modes Measurement

Traditional bridge inspections are performed by using tap tests, which is a good example of local mode excitation and local mode observation. Tapping that excites the entire structure is not useful in locating localized damage. This explains why inspectors must go through significant trouble to reach hot spots.

2.2.1 Laboratory testing on a bridge model

The tests for two bridge modes were performed at the laboratory in Institute of Mechanical Engineering, Haerbin, China. A bridge model (figure 2.1) is built to test the effects of cutting a diagonal member on the local and global mode vibration. The model consists of 8 1-m long sections. Each section is .8m in height and .5m in width. The vertical members are 30mm x 10mm in the section, and 766mm in length, except for member 15 and 21 (total 4 of two sides) are 748mm in length; the horizontal members are 8 mm x 10mm x 998 mm. The diagonal members are 30mm x 10mm x 1209 mm. The horizontal bars that join the two trusses are 30mm x 10 mm x 484 mm. And the diagonal cross braces on top and bottom of the truss are 30 mm x 2 mm x 1046 mm (Guo at al, 2008).

A 2kg weight fastened in the center of the geometry of the bridge model to create an initial displacement and then was suddenly released to excite the vibration of entire model (global modes), which was measured by a force-balance-accelerometer located in the center. Local modes were excited in the same way, but with a 0.1kg weight for each of the testing members and measured by using the piezoelectric accelerometers. Two types of the notches in the middle of the diagonal beam E26 were created to simulate damage to the member. The first notch is 3m deep and 2mm wide and the second one is 6mm deep and 25mm wide, which represent removal of 2% and 50% of the cross section, respectively.

Figure 2.2 shows the power spectra obtained from the accelerometer at the center of the beam that joins the two trusses on the bottom of the model. Case 1 denotes the health structure; case 2 and case3 denote models where the member E26 has been cut with a 3mm x 2mm and 6mm x 25 mm notches, respectively. The first global mode appears at 19.63 Hz. It can be seen that there are no changes at all for the global mode for the three cases, which means the notches in the diagonal member E26 cannot be detected by the global mode.

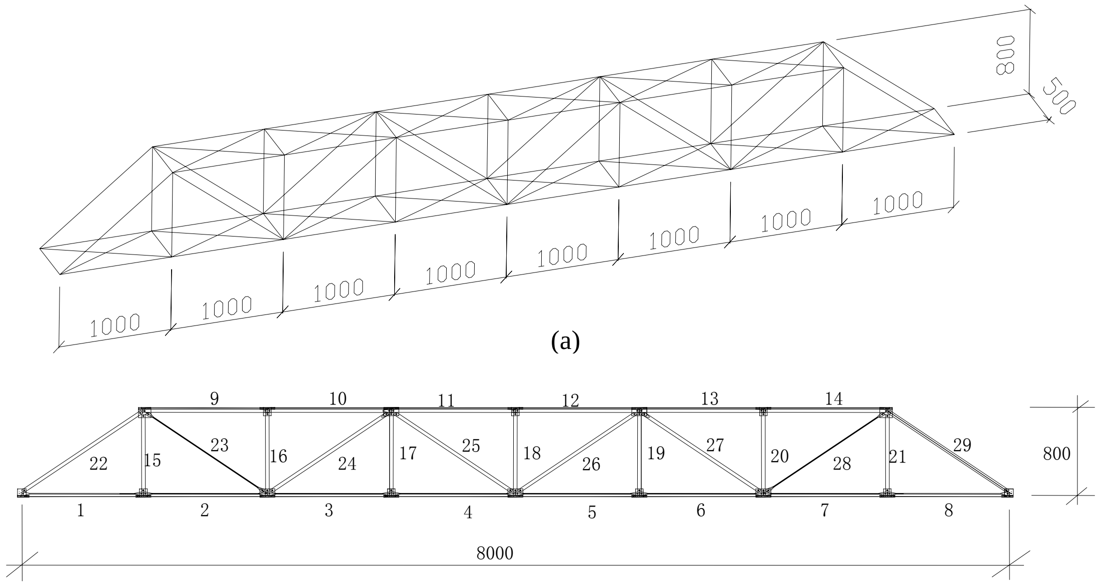

Figure 2.1 The bridge model: (a) the outline and dimensions, and (b) the horizontal view of the model and its parts' numbers.

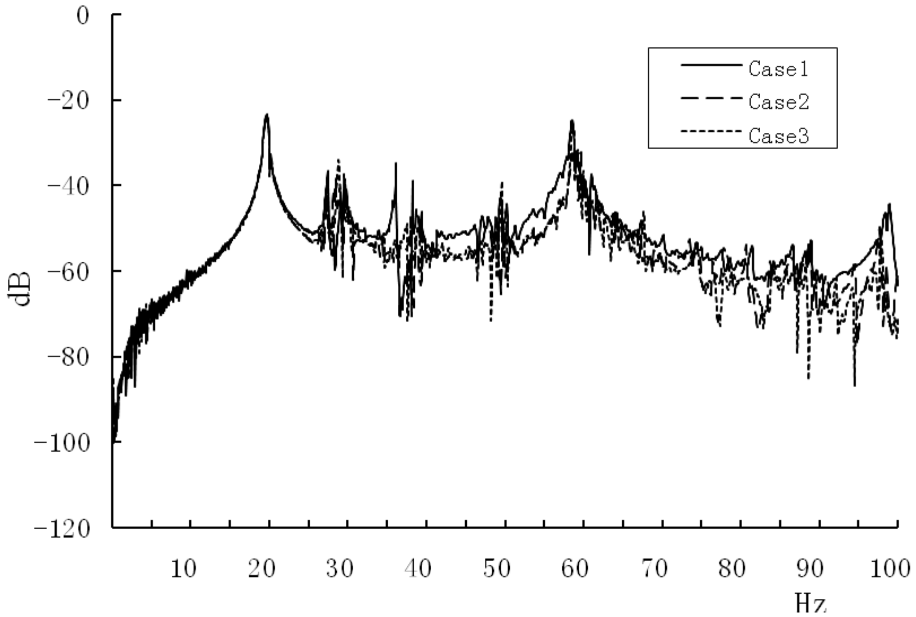

Figure 2.2 Power spectra of the first global mode (19.63 Hz) for 3 cases: (a) solid line: no cuts for two symmetric diagonal beams E26 and E26s; (b) dash-line: only E26 with a notch of 3mm in depth, 2mm in width; (3) dot-line: the cut for E26: 6mm in depth, 25mm in width, leave E26s intact.

When the diagonal element E26 is excited by removing the 0.1kg weight, the accelerometer on member E26 shows a shift in the main frequency peak as the cross section is progressively cut (Figure 2.3 (a) to (c)). This peak is associated with the flexural vibration of the diagonal member. In Figure 2.3, E26 denotes the diagonal member that has been cut, and E26s is the member at the same position on the parallel truss. E26s is not cut throughout the experiment.

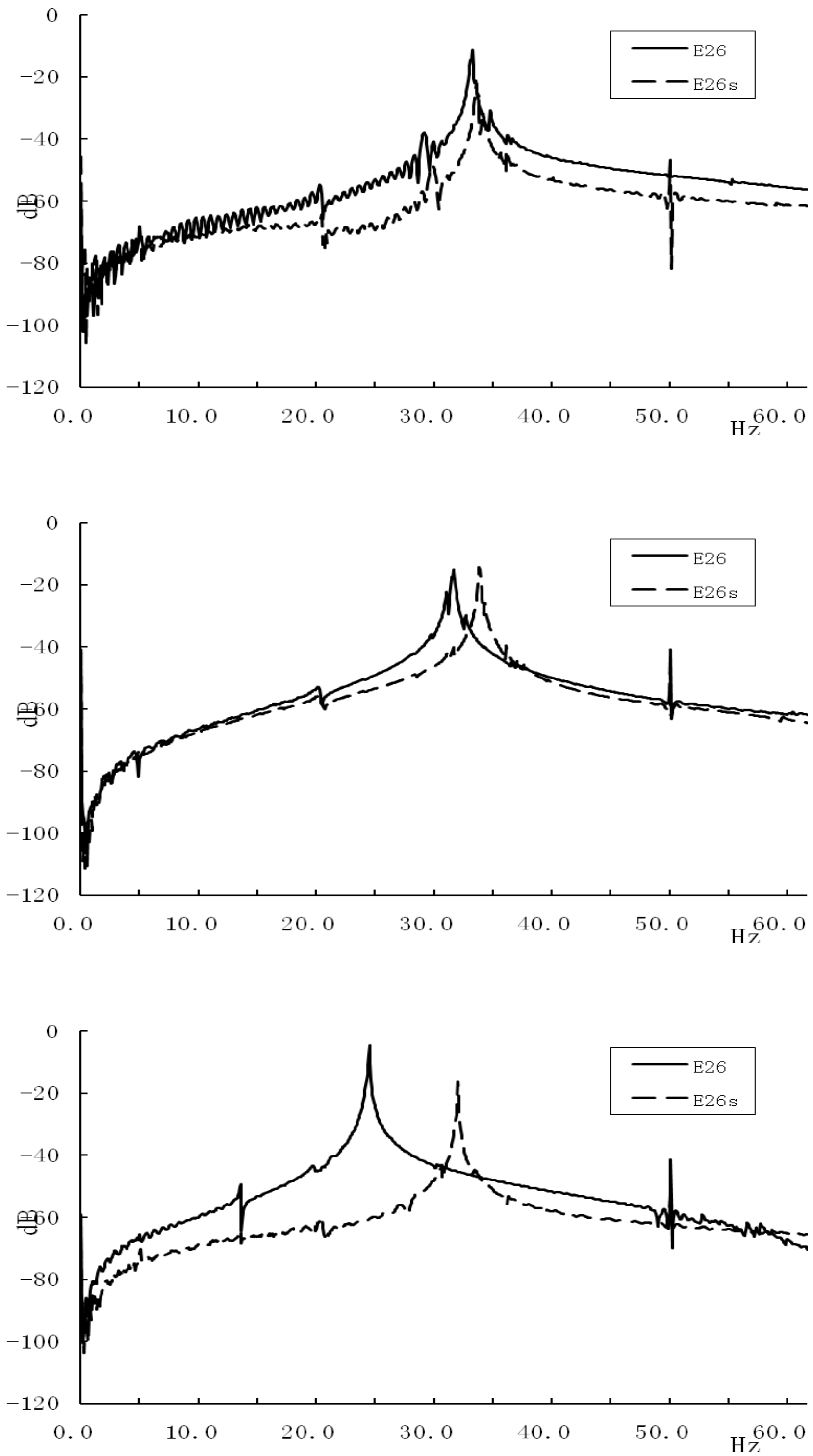

Figure 2.3 Power spectra of the first local mode of two symmetric diagonal beams E26 and E26s: (a) no cuts for both, (b) E26 with a notch of 3mm in depth, 2mm in width; (3) the cut for E26 was extended to 6mm in depth, 25mm in width, leave E26s intact.

2.2.3 Laboratory testing on the other bridge model

A one to eight (1:8) bridge model of a 48m long steel-frame bridge is also built up for the tests (figure 2.4). The model has sex 1-m long sections and a height of 0.5m in high and a width of 0.25m. The members are made of 30 mm by 3 mm and 25 mm by 3 mm steel angel-bars. Six force-balance type accelerometers were installed on the two low beams, E_4-E_5 and E'_4-E'_5 in the section 4 (from left) of the model. A heavy ball fastened in the middle of the beam E4-E'4 was dropped suddenly to create a vibration by the initial displacement. The tests were made repeatedly to record the vibrations of the global bridge and the local beam before cutting. For comparison with the first model, the testing results taken from the paper by Qi et al (2005) are presented in following.

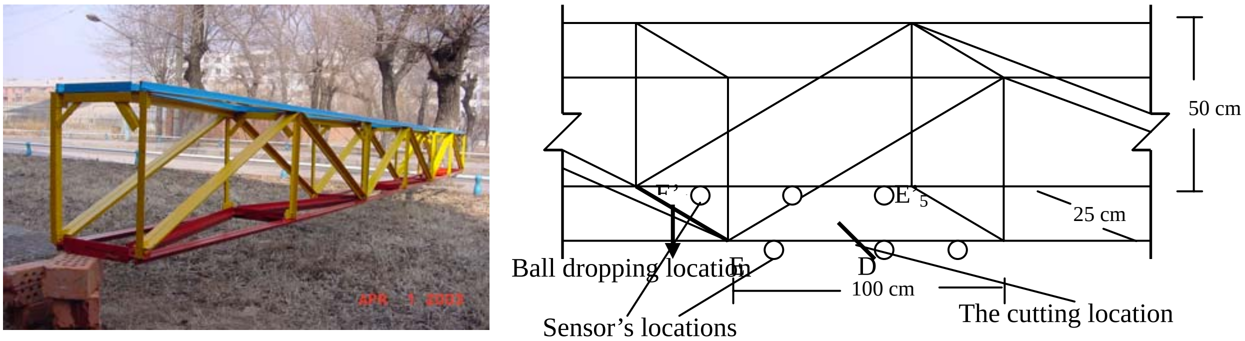

Figure 2.4. The steal bridge model: the photo and the section 4 from the left showing (1) the 6 accelerometers' locations and (2) the section dimensions: 100 cm in length, 50 cm in high and 25 cm in width.

Then the cuts are made on the middle of the beam E4-E5 by 25%, 50% and 75% in the area of its section, leaving the beam E'4-E'5 intact to simulate damage, and the vibration tests are repeated.

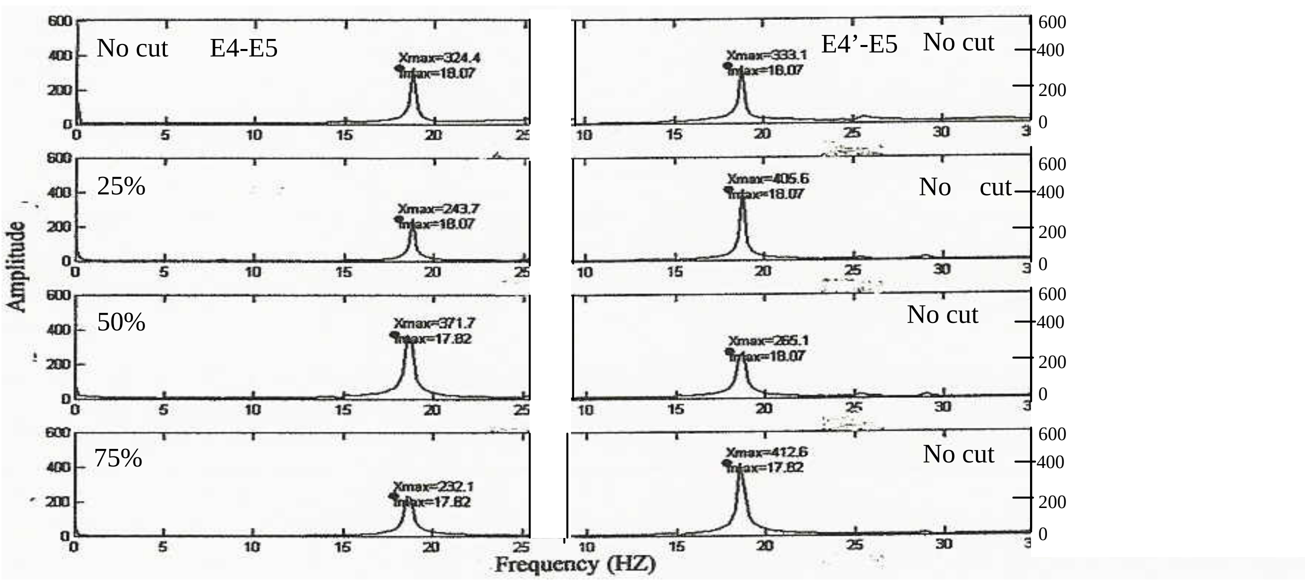

Figure 2.5. Fourier Spectrum of first global mode of acceleration recorded on the two beams with one cut (left) and the other intact (right).

Analysis of the recorded acceleration shows two frequency peaks: one at approximately 19 Hz and the other at approximately 76 Hz. Finite element analyses show that the 19 Hz mode corresponds to the first global mode of the bridge. The 76Hz peak coincides with the first mode of the beam E4-E5/E4'-E5', a local mode that involves only members E4-E5 and E4'-E5'. To examine the change in the measured vibration caused by the simulated damage, Fourier spectra of the global modes are obtained as shown in Figures 2.5. Member E4-E5 on the left side of the figure is the member with the simulated damage, and the E4'-E5' has not been cut. As in the case of the first model, figure 2.5 shows that no significant changes in the frequency of the first global mode in either beam can be observed in model 2, even when 75% of E4-E5 has been cut.

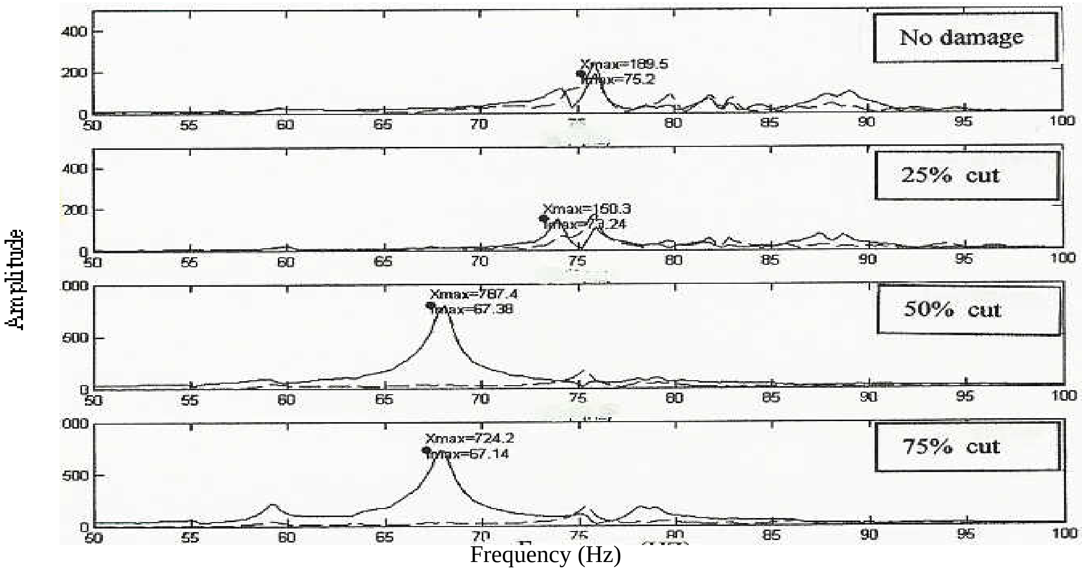

Figure 2.6. The changes in spectrum of the first local mode of acceleration recorded on the two beams with one damaged (E4-E5: solid lines) and the other intact (E'4-E'5:dash lines).

Figure 2.6 shows the Fourier spectrum of the first local mode for the two beams, E4-E5 (solid lines), and E4'-E5' (dash lines). The obvious changes in the frequency of the first local mode of the beam with simulated damage (solid lines) can be observed. Figure 2.6 shows that the beam with no damage has no change in the local vibration. Before damage was induced, the acceleration of both beams peak at around 76 Hz as depicted by the peak of the solid and the dashed lines. As E4-E5 is cut, the local frequency shifts significantly from 76 Hz to 69 Hz. The changes in frequency of both the local mode and the global mode for the beam with simulated damage are also plotted in figure 2.7.

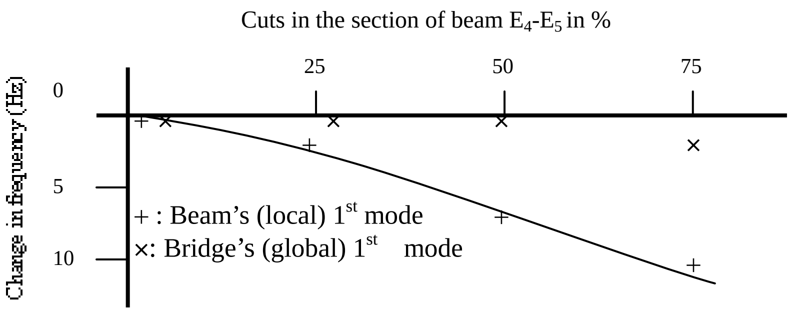

Figure 2.7: Changes in frequency with one beam E_4-E_5 cut and beam E'_4-E'_5 no cut.

The results of the experiments using the two bridge models illustrates that the global modes are not sensitive to the local damage. Changes in the local modes of the members where the damages occur, however, can easily be identified. Detection of structural damage, therefore, requires that local modes of damaged member are excited by the vibration.

3. DIFFICULTY IN MAKING LOCAL MODES MEASUREMENT

The major difficulty of making local modes measurements is due to the difficulty in exciting local modes in a structure, especially if the structure is large and complex. The difficulty in exciting local modes is because (1) the vibration of a local member in a structure usually is secondarily excited by its main structure under the ambient loading, and (2) the higher modes to excite, the more energy to need.

A comparison of the vibration of a local element and the global structure can be illustrated by using a simple steel frame as shown in Figure 3.1. Assume that member AB is attached to the frame by frictionless pins. When the structure is excited by a base acceleration, Member AB is excited through the forces at Joints A and B. Let f_i^l and c_i^l represents the frequency and the damping ratio of the mode i of the local element, respectively. Then, if the modes are uncoupled, then the equation of motion of beam AB can be written as

$$\ddot{x}_l + 2\pi f_i^l c_i^l \dot{x}_l + (2\pi f_i^l)^2 x_l = f(t),$$

$$f(t) = \mathrm{Sin}\,(2\pi\, f^{\,g}\, t)\,, \qquad -\infty < t < \infty. \tag{3.1}$$

The solution can be written as:

$$x_l = A_l Sin(2\pi f^{\,g} t) + B_l Cos(2\pi f^{\,g} t), \qquad \infty < t < \infty, \tag{3.2}$$

where l and g in sub/superscript represent the local and the global modes, respectively.

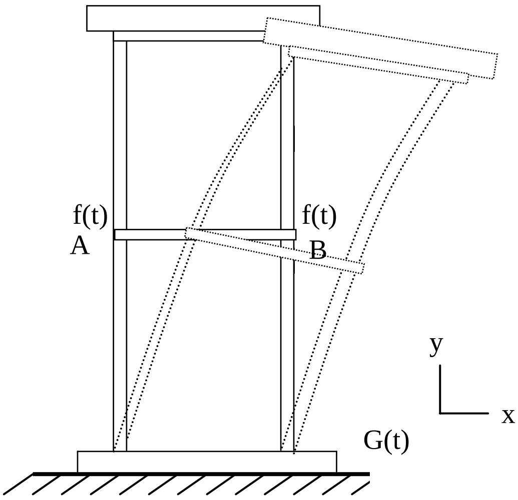

Figure 3.1. Rectangular steal frame, main structure, and local beam AB

The ratio of the energy of the responses $x_l(t)$ to the excitation input $f(t)$ can be obtained:

$$A_l^2 + B_l^2 = \frac{1}{16\pi^4 f_i^{l^4}\left(\left(1-\dfrac{f^{g^2}}{f_i^{l^2}}\right)^2 + \left(c_i^l \dfrac{f^{\,g}}{f_i^l}\right)^2\right)}. \tag{3.3}$$

Usually the modal frequency of the local member is much greater than that of the main structure, i.e. $f_i^l >> f^{\,g}$, equation (3.3) be approximated by:

$$\left(A_l^2 + B_l^2\right) = \frac{1}{16\pi^4 f_i^{l^4}}; \tag{3.4}$$

Equation 3.4 shows the percentage of energy from f(t) imparted to member AB is a small fraction of input energy, as f_i^l is usually much greater than 1. As $f_i^l = f^g$, i.e. the excitation frequency reaches the resonant frequency of beam AB, the energy of the local mode reaches its maximum level of

$$\left(A_l^2 + B_l^g\right)_{\max} = \frac{1}{16\pi^4 f_i^{l^4} c_i^{l^2}} \tag{3.5}$$

Equations 3.4 and 3.5 show that the local modes can be excited when the frequency of the main structural vibration approaches the natural frequency of the local member. This means that much higher frequencies of the main structure vibration are demanded to excite the local modes. Unfortunately, the following analysis shows that much more energy is needed to excite the higher frequencies' modes of the main structure.

Assume that the ambient loading to main structure *G(t) = Sin (2πft).* The ratio of the energy of the structural responses $x_g(t)$ to the excitation energy from input *G(t)* can be obtained as:

$$\left(A_g^2 + B_g^2\right)_{r\max} = \frac{1}{16\pi^4 f_i^{g^4} c_i^{g^2}} \tag{3.6}$$

where *g and i* represent main structure and its vibration modes; subscript r represents the ambient input frequency approaches to the natural frequency of main structure. Equation 3.6 shows that the maximal energy excited by the ambient loading will decrease with increasing of $f_i^{g^4}$. This means the higher modes of a structure to excite, much more energy to need**.** Exciting a structure with such level of energy is not practicable in real life. Even if it can be achieved, the structure will suffer significant damage as a result of such excitation.

4. CONCLUSIONS

1、In order to successfully detect damage in a structure the damaged member must be vibrated in its own mode.
2、Only a small percentage of the input energy to the structure's excitation contributes to the local member vibration, therefore, local modes of the members' vibration are not easily excited.
3、When the damaged member vibrates in its own mode, the damage can be readily detected.

AKNOLEGEMENT

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REFERENCES

Fritzen C.P. and K. Bohle (2001): Vibration-based global damage identification –A tool for rapid evaluation of structural safety, *Structural Health Monitoring, Edited by Fu-Kuo Chang*, pp849-859, CRC Press.

Gao Y. and B.F. Spencer (2002): Damage localization under ambient vibration using changes in flexibility, *Earthquake Engineering and Engineering Vibration*, Vol. 1, No.1.

Gao Z.M, et al. (2001): Study on vibration based damage detection of Ji-Shui Gate bridge in Hong Kong, *Earthquake Engineering and Engineering Vibration in Chinese*, Vol.21, No.4. pp117-124.

Guo X. et al (2008): Symmetrical signal and its application in structural damage detection, *Proceedings of 14 WCEE, Beijing, China.*

Hou Z. et al, (2000): Wavelet-based approach for structural damage detection, *Journal of Engineering Mechanics, Vol. 126, no. 7,* pp 677-683.

Pei Q., X.. and M. Chang X. (2003): A Review of health monitoring and damage detection of bridge detection, *Earthquake Engineering and Engineering Vibration in Chinese*, Vol.23, N0.2, pp105-113.

Lian Z. and G.C. Lee (2001): A new parameter of vibration signature analysis for large elastic structure, *Structural Health Monitoring, Edited by Fu-Kuo Chang*, pp393-402, CRC Press.

Isoda H, et al. (2001): Modeling and measurement for health monitoring of an existing SRC 8-story building, *Proceedings of SPIE on Smart Structures and Materials*, Vol. 4330, pp77-84.

Loh C.H. and S.C. Chien (2001): Identification of damping and stiffness matrix of building structure from response measurement, *Proceedings of SPIE on Smart Structures and Materials*, Vol. 4330, pp85-96.

Park G. et al, (2000): Impedance-based health monitoring of civil structural components, *Journal of Infrastructure System, Vol. 6, no 4,* pp153-160.

Qi G. Z. et al, (2005): Local measurement for structural health monitoring, *Earthquake Engineering and Engineering Vibration, Vol.4, no. 1,* pp165-172.

Shinozuka M., et al. (2004): MEMS-based wireless real-time health monitoring of bridges, *Proceedings of the Third International Conference on Earthquake Engineering – New Frontier and Research Transformation*, October 19-20, 2004, Nanjing, P.R. China, pp2-6.

Shinozuka M. at al. (2000): Feasibility of damage/change detection in civil structure by

SAR, *Proceedings of SPIE on Smart Structures and Materials*, Vol. 3988, pp165-175.

Tong M. et al, (2005): Time derivative of earthquake acceleration, *Earthquake Engineering and Engineering Vibration*, *4Vol.4, no.1*, pp 1-16.

Vecchio A. and H.V. Auweraer (2001): An experimental Validation of a model-based approach in damage detection and localization, *Structural Health Monitoring, Edited by Fu-Kuo Chang*, pp957-966, CRC Press.

Xu N. et al, (2004): A wireless sensors network for structural monitoring, *Proceedings of the 2nd International Conference on Embedded Networked Sensor System, Baltimore, MD, USA 2004,* pp 13-24.