HEALTH MONITORING OF BUILDING USING SEISMIC INTERFEROMETRY

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ABSTRACT

The objective of the health monitoring of building using seismic interferometry is to clarify the reliability and effectiveness of the deconvolution interferometry to recognize and to identify damages in buildings due to the loss of stiffness after earthquakes to mitigate disaster risk. Therefore, the analysis procedure has been divided into three cases. Case A is the study of the technique validation by visual inspection of the annex BRI building suffered from the Great East Japan Earthquake. Case B illustrates the applicability to Sakishima Office high-rise Building to detect damages and shear stiffness estimation. Case C indicates the evaluation of the sloshing effect into the experimental wooden sixth-story building.

The methodology demonstrated here, provides the analysis of strong motion and ambient vibration data to evaluate the dynamic properties of the building in the time periods before, during and after the quake to estimate damages and loss of shear stiffness, using system identification as a tool for seismic interferometry. Moreover, to assess the changes in the dynamic parameters due to the sloshing water effect.

By comparison of the results in the time periods before and after the quake, using ambient vibration, the shear wave velocity degradation located in each floor is assessed. The overall tendency on Case A indicates the dependency of the shear wave velocity degradation with the width of cracks. Case B shows the well estimation of shear stiffness and dependence of its accurateness due to the number of sensors. Case C shows that seismic interferometry is a suitable technique and has high sensitivity to evaluate the wave patterns to estimate the sloshing effect.

Keywords: Health Monitoring, System Identification, Seismic Interferometry, Sloshing Effect.

1. INTRODUCTION

Structural health monitoring (SHM) is defined as the tracking of the structural condition, and detects damages in the buildings through observation of the changes in the wave patterns, which are expressed regarding changes in the geometry and mechanicals material properties. While those damages are well-defined as unforeseen changes in the system, which tends to modify parameters such as wave traveling time, shear wave velocity, stiffness, etc., caused by natural disaster or human events, leaving those structures to expose to the risk.

Early detection and identification of the damages in the structures are the critical tasks that the engineering must cope with. Therefore, due to the exhibited risk a quick methodological implementation for health monitoring of buildings and infrastructures are needed.

The principal feature that SHM must have is to enable to deliver enough accuracy in the estimated parameters that reveal the structural integrity and safe level of the building, owing to data used to incorporate risk management strategies (Early Warning System) and structural rehabilitation, as well as the updating of seismic code.

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On the other hand, efficient, prompt detection of the damages gives the chance to reduce the loss of life and to reestablish the characteristics of the building before the damages progress, and the repairing procedure becomes economically unviable.

2. FUNDAMENTALS OF DIGITAL SIGNAL ANALYSIS AND PROCESSING

2.1. Seismic Interferometry

The term interferometry is ordinarily related to the study of interference phenomena between pairs of receivers that capture a signal, to acquire information from the source, medium and the differences between them (Andrew Curtis, 2008).

SHM of a building is necessary to separate building response to an earthquake from soil-structure coupling and wave propagation below the base of the building because building response has been contaminated with them. Seismic interferometry based on deconvolution is a method to unravel the building response and later estimate the wave velocity which travels through the building (Nori Nakata, 2013).

In arithmetic, deconvolution is described as a set of rules funded in the procedure to reverse the effects of convolution on a recorded signal. The goal of deconvolution is to recover the first signal before it has been contaminated with noise. In other words, it is to extract the pure response of the building regardless of ground coupling (Nori Nakata, 2013).

The following procedure to describe mathematically the deconvolution interferometry is based on the paper of Nori Nakata et al. (2013) funded on Snieder and Safak (2006):

$$\begin{aligned} u(z) &= \sum_{m=0}^{\infty} S(w)R^{m}(w)\left\{e^{ik(2mH+z)}e^{-\gamma|k|(2mH+z)} + e^{ik(2(m+1)H-z)}e^{-\gamma|k|(2(m+1)H-z)}\right\} \\ &= \frac{S(w)\left\{e^{ikz}e^{-\gamma|k|z} + e^{ik(2H-z)}e^{-\gamma|k|(2H-z)}\right\}}{1-R(w)e^{2ikH}e^{-2\gamma|k|H}} \end{aligned} \tag{1}$$

when the height of the building is H, the recorded signal of an earthquake in the frequency domain at an arbitrary receiver at height z is given by Eq. (1), where S(w) is the incoming waveform to the base of the building, R(w) is the reflection coefficient related to the SSI and foot of the building, k is the wavenumber, γ is the attenuation coefficient, and i the imaginary unit.

The input waveform S(w) includes the information of the earthquake and the effect of propagation such as attenuation and scattering along the path from the hypocenter to the foundation of the building while the attenuation coefficient γ is denoted by $\gamma = \frac{1}{2Q}$ with Q as the quality factor.

Eq. (1) with m = 0, the first term $S(w)e^{ikz}e^{-\gamma|k|z}$ indicates the incoming upgoing wave and the second term $S(w)e^{ik(2H-z)}e^{-\gamma|k|(2H-z)}$ the downgoing wave, which is reflected off the top of the building. Therefore, m represents the number of reverberations between the base and the top of the building.

In order to attain the impulse response of the building at the level z by deconvolution at the location of reference (z_a), it is introduced the Eq. (2). The summation term in the Eq. (2) is represented the Taylor Expansion. In this case the receiver at the location z_a works as a virtual source:

$$\begin{aligned} D(z,z_a,w) = \frac{u(z)}{u(z_a)} &= \frac{S(w)\left\{e^{ikz}e^{-\gamma|k|z} + e^{ik(sH-z)}e^{-\gamma|k|(2H-z)}\right\}}{S(w)\{e^{ikz_a}e^{-\gamma|k|z_a} + e^{ik(2H-z_a)}e^{-\gamma|k|(2H-Z_a}\}} \\ &= \sum_{n=0}^{\infty}(-1)^{n}\left\{e^{ik(2n(H-z_a)+z-z_a)}e^{-\gamma|k|(2n(H-z_a)+z-z_a)}\right. \\ &\quad \left. + e^{ik(2n(H-z_a)+2H-z-z_a)}e^{-\gamma|k|(2n(H-z_a)+2H-z-z_a)}\right\} \end{aligned} \tag{2}$$

however, Eq. (2) is unstable due to the spectral division. Therefore, Eq. (2) needs regularization by parameter ε making (Nori Nakata, 2013):

$$D(z, z_a, w) = \frac{u(z)}{u(z_a)} \approx \frac{u(z) * u(z_a)}{|u(z_a)|^2 + \varepsilon \langle |u(z_a)|^2 \rangle} \tag{3}$$

where * is a complex conjugate and $\langle |u(z_a)|^2 \rangle$ the average power spectrum of $u(z_a)$. In general, ε take the value of 1% (Nori Nakata, 2013). It is shown that the deconvolution presented in Eq. (2) is independent of the incoming waveform S(w) and the ground coupling R(w).

When $z > z_a$, Eq. (2) depicts a wave that is excited at z_a (base of the building) and reverberated between the bottom and the top of the building. Using the normal-mode analysis of deconvolution interferometry, Eq. (2) is based on the summation of normal-mode waves and applying the contour integration proposed by Snieder and Safak (2006) (Nori Nakata, 2013). Then, using the inverse Fourier transform to $D(z, z_a, w)$ is possible to attain the expression to define the fundamental mode using shear wave velocity (c):

$$T_0 = \frac{4(H - z_a)}{c} \tag{4}$$

3. HEALTH MONITORING SYSTEM OF BUILDING

3.1. Case A: Annex BRI Building

Study Case A has the objective to show the reliability of deconvolution interferometry on how the system is identified to detect structural damages through tracking the shear wave velocity in the Annex BRI building and to validate its results by visual inspection in the Great East Japan Earthquake on March 11th, 2011, where the structure was affected in each floor by several secondary structural damages, such as flexural and shear cracking on columns and shear walls, respectively (see Figure 1). Moreover, several cracking patterns affected the slab in each floor.

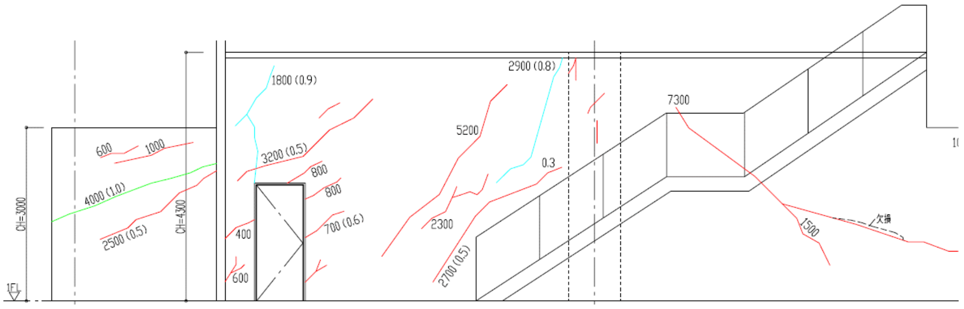

Figure 1. Cracking patterns on west entrance lobby. Numbers show length and width of cracks related to Figure 2.

As reported by SHM and visual inspection on the Annex BRI building and to validate the technique to detect damages, it is possible to relate the cracking to the shear wave velocity degradation according to Figure 2.

Regarding Figure 2 it is found that increment of the cracking in walls and columns increase the shear wave velocity degradation on the north-south direction. From the 1st to the 4th floor, the cracking pattern declines (0.2 mm to 0.8 mm) as the shear wave velocity degradation in agreement. While from the 4th to the 6th floor, the shear wave velocity degradation increased as well as the cracks pattern (0.2 mm to 0.8 mm). On the other hand, on the 7th floor, the shear velocity degradation decreased due to the reduction of the cracking. Besides, at the same time, the growth of the shear wave velocity degradation with the increment of the width cracks between 0.2 mm and 0.8 mm according to the chart in Figure 2 is recognized. Therefore, the width crack has a significant effect in the shear velocity degradation. Due to these facts, the seismic interferometry is suitable to perceive and to identify damages through the shear wave velocity to travel inside of the building.

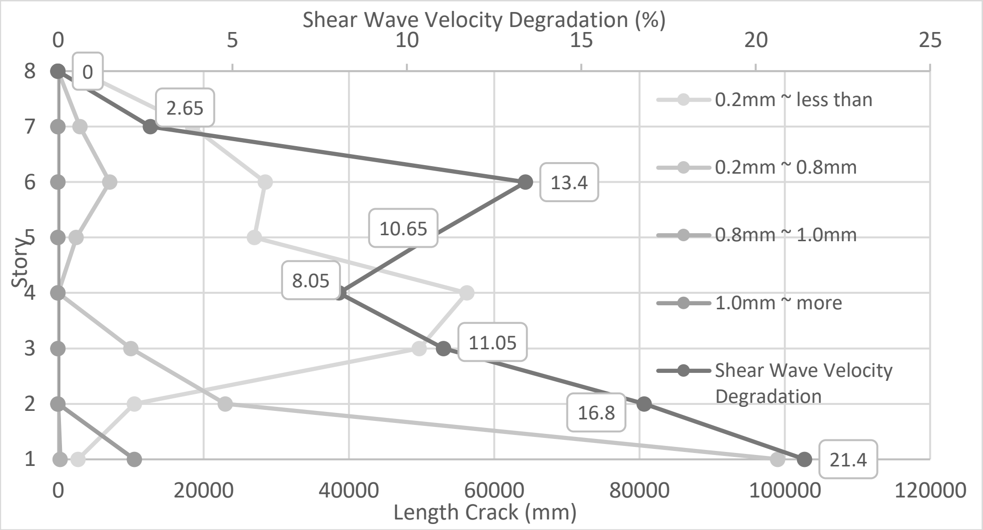

Figure 2. Relationship between shear wave velocity degradation and length cracks per stories on the north-south direction.

3.2. Case B: Sakishima Office High-Rise Building

Case B has the task to reveal the effectiveness and usefulness of the seismic interferometry to estimate shear stiffness. The building is analyzed using the Great East Japan Earthquake on March 11th, 2011 and ambient vibration data before and after the shake. Consequently, Figure 3 indicates the estimated shear stiffness by ambient vibrations before and after the quake on the X direction in Sakishima Office and compares with shear stiffness designed. While Figure 4 illustrates the average designed stiffness and its variation per floor.

Figure 3 reveals a well estimation of the shear stiffness from the 52nd to the 18th floor by ambient vibrations, when the stiffness variation in each story is similar. However, when the shear stiffness in the lower stories increments drastically due to the design (see Figure 4), in another word, the shear stiffness considerably changes among stories, the utilization of the more accelerometers to increase the accurateness is necessary. Thus, the location of two sensors among the 1st and 18th determines a low accuracy of the shear stiffness owing to high stiffness variation.

3.3. Case C: Experimental Wooden 6F Building

Case C discusses the sloshing effect due to the temporary water pools using seismic interferometry. Normally, the evaluation of the fundamental period, increasing the load into the building increment it. Consequently, Figure 5 in the East-West direction reveals the rise of the natural period observed from the ambient vibrations measured. It can be appreciated in the increment of the dispersion in the grey wave, increasing the wave traveling time, reducing the shear wave velocity (Eq. (4)). However, North-South direction illustrates decrement of the natural period. Because the grey wave shows the decrement in the wave traveling time, increasing the shear wave velocity (Eq. (4)). This drop and growth in the fundamental period are specially called sloshing water effect. It was reported by George W. Housner, who studied the dynamic behavior of the water into the tanks during the Chilean earthquake of May 1960. On the other hand, it is appreciable the wave's shape changed, which is expressed as reducing its amplitude and increment of the dispersion. It phenomenon is associated to the attenuation factor growth.

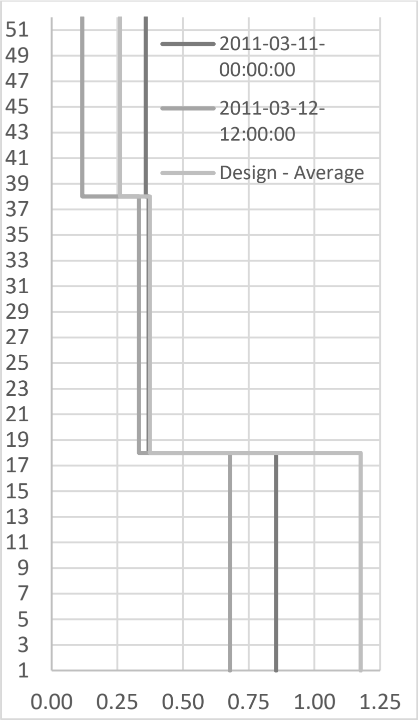

Figure 3. Shear stiffness on X direction (10^9N/m).

Figure 4. Shear stiffness on X direction due to design (10^9N/m).

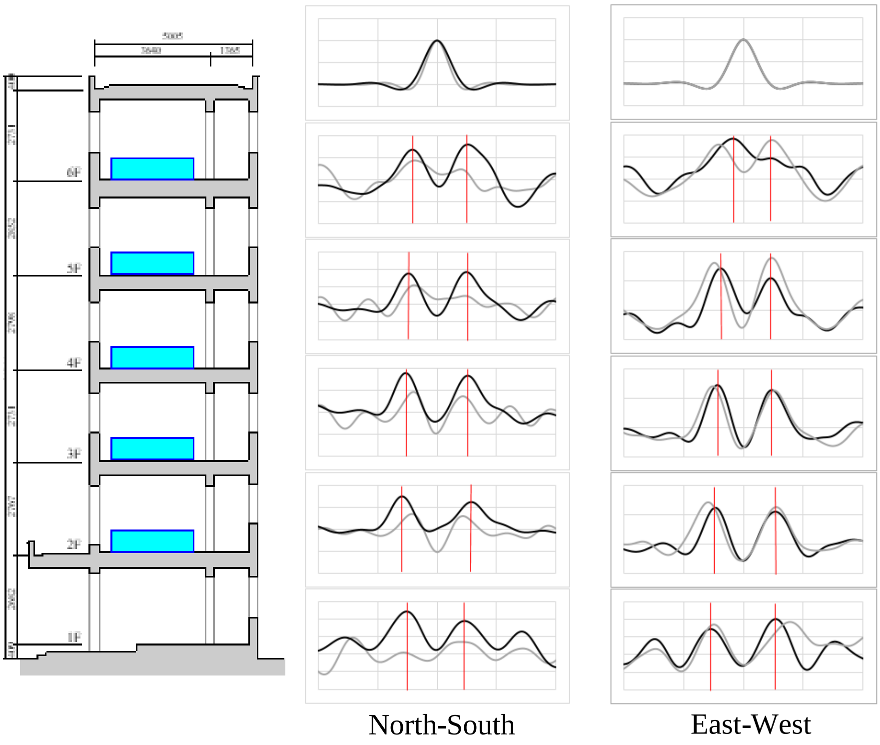

Figure 5. Variation of wave patterns. The black line shows the behavior without additional load, while the grey line illustrates the wave conducts with extra load (water pool).

CONCLUSIONS

Case A reveals the reliability, high sensitivity, and effectiveness to detect damages using the shear wave velocity propagation through the building. The validation of the method by visual inspection illustrated the closeness that exists between cracking patterns and shear wave velocity degradation, furthermore, the strong dependence of the shear wave velocity of width cracking. However, the estimated dynamic properties during the earthquake could address to overestimate dynamic parameters due to the magnitude of the damages. It is because of the degradation of the shear wave velocity owing to bending, shear, torsional and open and close of cracking patterns during the quake.

Case B illustrated the well-balance in the applicability of the deconvolution interferometry to estimate the shear stiffness through the shear wave velocity. However, it has shown a high dependence on the number of sensors with regards to a drastic variation of the design stiffness. Thus, it is necessary to have more sensors to capture improvement in the accurateness of the estimated results.

Case C indicated critical agreement of the estimated dynamic parameters by seismic interferometry due to capturing of the sloshing water effect and was in coherence with G. Housner. Therefore, it can explain the amplification and reduction of the natural period in the experimental wooden Sixth-Storied Building. Hence, the seismic interferometry is an appropriate technique to study the building responses, to detect damages and to assess sloshing effect due to the reconstruction of the wave interference patterns.

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