17th World Conference on Earthquake Engineering, 17WCEE
Sendai, Japan - September 27th to October 2nd, 2021

HEALTH MONITORING OF BUILDING USING SEISMIC INTERFEROMETRY

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Abstract

The major issue after a huge earthquake is to know the remain status of the building quickly to assess the option to evacuate it, reducing possible causalities due to aftershocks or localized collapses. Therefore, an early identification of the damages in the structure is the critical task that the engineering must cope with. Thus, owing to the exposure and vulnerability a rapid methodology for Structural Health Monitoring (SHM) is crucial. SHM is defined as the tracking of the structural conditions and detecting damages in buildings through the surveillance of the changes in the wave patterns, which are expressed regarding changes in the geometry and mechanical properties, while those damages are defined as unforeseen changes in the system, which tends to modify dynamic parameters, caused by natural disaster and/or human events. The principal feature that SHM must have is to enable and to deliver enough accuracy in the parameters that reveal the integrity and safety level of the building, to incorporate disaster management strategies and policies. Health monitoring of building using Seismic Interferometry (SI) is a tool for system identification to detect and localize damages in buildings. SI based on deconvolution is a method to unravel the building response, in other words, it extracts the soil-structural interaction and allows to estimate the shear wave velocity traveling through the building.

In this study, it is considered three building cases to demonstrate the reliability and effectiveness of this techniques to detect damages, and to use this not only as instrument for building assessment and to generate rehabilitation or retrofitting plans, but also to implement it as tool for early warning system.

The first case on SRC-Annex BRI Building validated the technique by correlation with cracking patterns. It enabled to clarify the relationship between cracking and shear wave velocity degradation (SWVD). It is found that the increment of cracking in walls and columns increase the SWVD in agreement. Validating the identification and localization of damages as well as the post-earthquake repairing processes.

The second case on Steel-Sakishima Office High-Rise Building revealed the effectiveness to estimate shear stiffness (SSF) when its variation in each story is similar. However, when SSF increases drastically, the implementation of more sensors to improve the accurateness is vital.

The last case on Experimental Wooden 6F Building showed an irregular wave traveling behavior, mainly due to wood anisotropy. However, the reconstruction of wave patterns allowed the evaluation of the dynamic's properties owing to the sloshing effect produced by the temporary water pools to simulate the live load. It showed the drop and growth in the fundamental period, the wave's shape changes, which is expressed as decreasing its amplitude and increment of dispersion. Further analysis has to be accomplished for wooden buildings.

These evaluations demonstrated that the technique has high sensibility to identify and locate damages in buildings constructed by steel reinforced concrete and steel frames, as well as the close relationship between shear wave velocity and cracking patterns. Additional analysis on masonry should be implemented. Moreover, the study shown a powerful dependency on number of sensors, only if the stiffness variation presented in the building is large within consecutive stories. On the other hand, using this approach is possible to verify the effectivity of repairing works. The SSF estimation allows to structural designers to know the key input parameter for retrofitting design and/or plans. SI on Wooden Building exhibited a complex traveling of shear wave velocity profile, likely due to the spatial variation of wood properties. However, it allows to assess the sloshing water effect.

Keywords: Health Monitoring; System Identification; Seismic Interferometry; Shear Stiffness; Sloshing Effect.

1. Introduction

The last megathrust earthquake in Chile has reveal the fragility of the building system, showing a common pattern of brittle damages on shear walls, frequent feature of rigidity design, which does not account for ductile behavior. As common question left amongst the engineering community, is to know the remain stiffness of the building to prevent further collapses and to stablish strategies and policies for disaster management. Health Monitoring represents a great chance for development and improvement of techniques that contribute to vulnerability assessment and risk mitigation.

SHM based on system identification allows to estimate dynamic properties and damages, in order to determine a suitable way to reestablish the design parameters and to prolong the structural lifespan. Early recognition and localization of damages in structures are a critical task that develop and developing countries must face with. However, developing countries have a larger effort to accomplish due to low resources investment and the lack of disaster management prioritization. Consequently, the motivation of this research reflects further efforts to contribute and influence disaster mitigation, directly addressed to developing countries.

Health monitoring is well-known as the tracking of the structural integrity and detecting damages in the structures through surveillance of the changes in the wave patterns, which are expressed regarding changes in the geometry and mechanical properties, while those damages are defined as unforeseen changes in the system, which tends to modify parameters such as wave traveling time, shear wave velocity, stiffness, etc., caused normally by earthquakes, leaving the system exposed to the risk. Therefore, due to the exhibited vulnerability a quick methodology for health monitoring of building and infrastructures is needed. On the other hand, an efficient and prompt detection of damages provide the opportunity to mitigate the loss of life and to reestablish the characteristic of the building before the damages progress and the restoring procedure becomes economically unviable.

1.1 Target buildings

Three buildings are scoped on this study and shown in Fig.1. Two middle-rise buildings and a high-rise building. The two first are located at Tsukuba and named SRC-Annex BRI Building, and Experimental Wooden 6F Building. The third one is placed at Osaka Bay and called Steel-Sakishima Office.

The Steel-Sakishima Office is 256 m high with 52 stories and 3 basements. It was constructed in 1995 on the coast of the Osaka Bay. The building has a total area of 10.968 m² and a total floor are of 149.752 m². It is supported by 400 steel piles with roughly 64 m embedded. Five tri-axial accelerometers are installed at four levels (1F, 18F, 38F and 52F), there is a sensor on each of the wings on the 52nd floor [1]. The Experimental Wooden 6F Building was built in 2016. It has a wooden framing structure with an building area of 38.95 m², a total floor area of 206.09 m² and an eaves height of 16.91 m. It is supported by 11 steel piles, each being 12 m fixed [2]. Around 18 tri-axial accelerometers were installed during its survillance period using two kinds of equipment. One half is a high-performance type equipped with

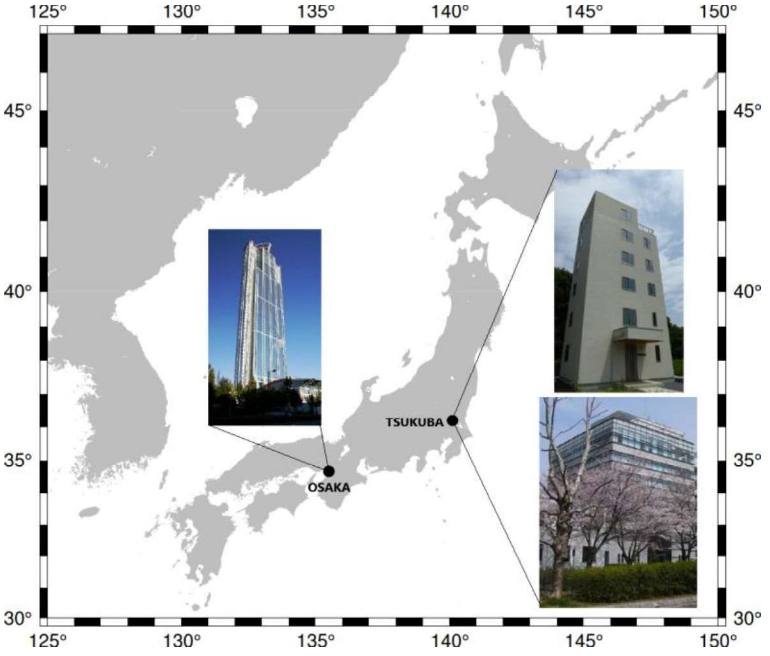


Fig. 1 – Target buildings locations.

tri-axial feedback. The second half is an econimical type equipped with tri-axial feedback MEMS sensor [3]. The SRC-Annex BRI Building is an Eight-Stories and a basement of Steel Reinforced Concrete (SRC) structure built in 1998. The building has an area of 637 m², a total floor area of 5.050 m² and 69.5 m tall. The building is supported by spreading foundation with around 8 m embedded. It has been intrumented with eleven tri-axial sensors.

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 [4].

In SHM of building is necessary to separate bulding response of an earthquake from soil-structure coupling and wave propagating 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 [5]. In arithmetic, deconvolution is descibed as a set of rules funded in the procedure to reverse the effect of convolution on a recorded signal. The goal of deconvolution is to recover the first signal before it has been polluted with noise. In ther words, it is to extract the pure response of the building regardless of ground coupling [5].

The following procedure to describe mathematically the deconvoltion interferometry is based on the paper [5] and funded on [6]:

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

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), were 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 presents 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 Eq. (2). The summation term in the Eq. (2) is representing the Taylor Expansion, In this case the receiver at the location z_a works as 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 [5]:

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

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 1% [5]. 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 [5] [6]. Then, using the inverse Fourier transform to $D(z, z_a, w)$ is possible to get the expression to define the fundamental mode using shear wave velocity (c):

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

On the other hand, using the equation of motion described by a single degree of freedom (SDOF) system in Eq. (5) is possible to find the fundamental period based on the stiffness:

$$m\ddot{x}(t) + c\dot{x}(t) + kx(t) = -m\ddot{x}_g(t) \tag{5}$$

for concept of simple computation and straightforward estimation of shear stiffness is assumed an undamped SDOF system for ambient vibration data processing. Then, the shear stiffness can be processed and assessed as:

$$k \approx \frac{\pi^2 m c^2}{4(H - z_a)^2} \tag{6}$$

3. Health Monitoring System of Building

3.1 Case A: SRC-Annex BRI Building

Study Case A has the objective to show the reliability of deconvolution interferometry on how the system is used to identify and localize damages through the tracking of shear wave velocity in the SRC-Annex BRI Building and to validate its results by correlation with the cracking patterns developed in the structure, such as flexural and shear cracking on columns and shear walls, by the 2011 Great East Japan Earthquake. Fig. 2 illustrates the cracking layout of the West-Entrance Lobby.

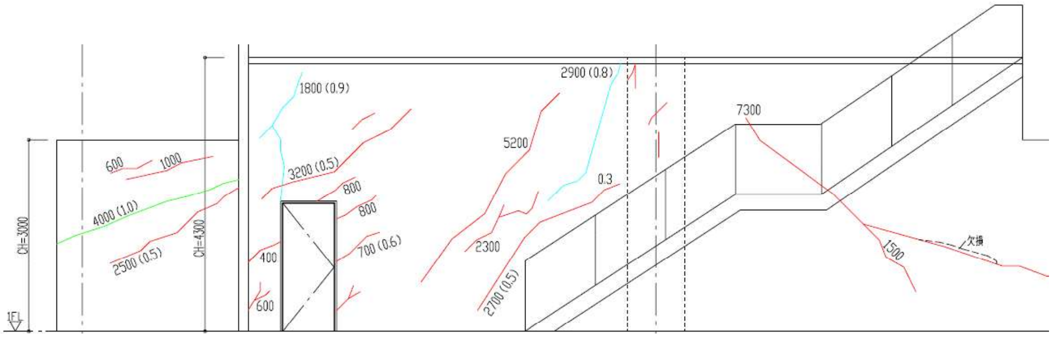


Fig. 2 – Scheme of cracking patterns on the West-Entrance Lobby. Red, light-blue, and light-green illustrate part of the crack width recognition during the survey study, which is summarized on Fig. 5 as correlation.

Fig. 3 shows the deconvolution interferometry on the SRC-Annex BRI Building and normalized at the first floor. It illustrates the upgoing and downgoing waves characterized as impulse response. Fig. 4 shows the shear wave velocity profiles after of applied the deconvolution interferometry. It is evidently identified the reduction of the parameter due to the damages caused by the earthquake. Red profiles represent the shear wave velocity after the earthquake, while dark-blue profiles the shear wave velocity before the event.

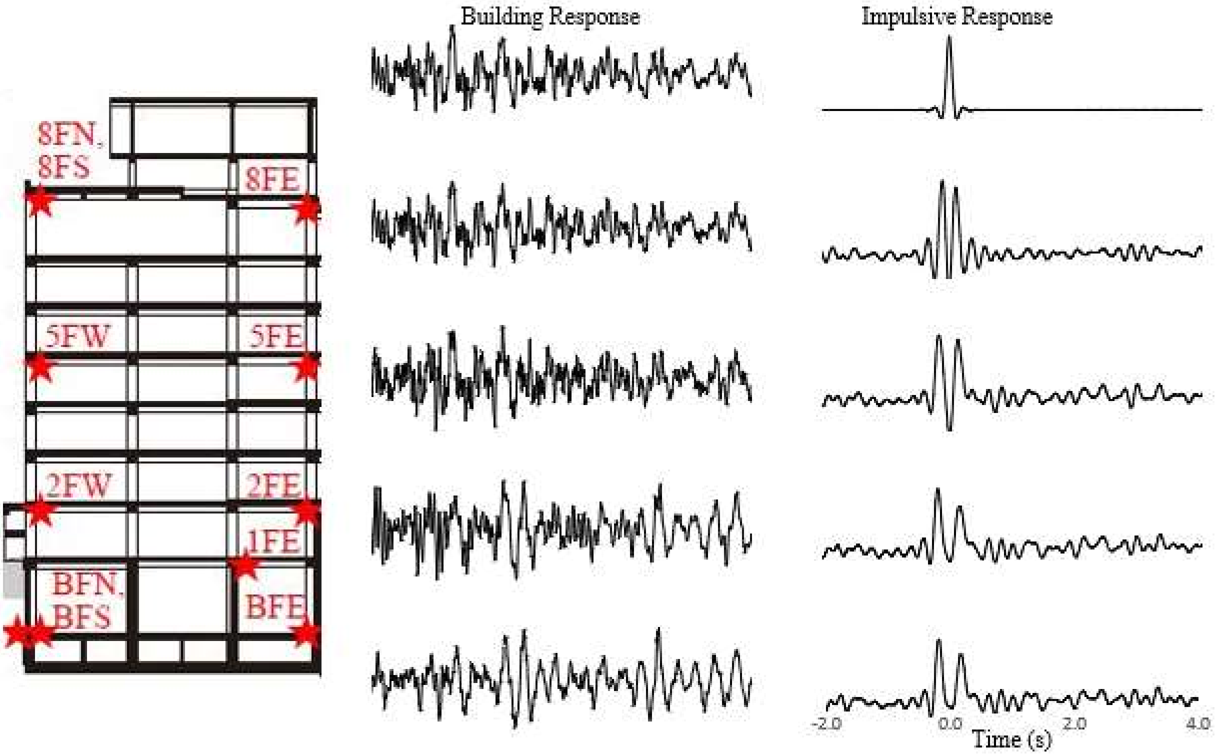


Fig. 3 – Seismic Interferometry on SRC-Annex BRI Building.

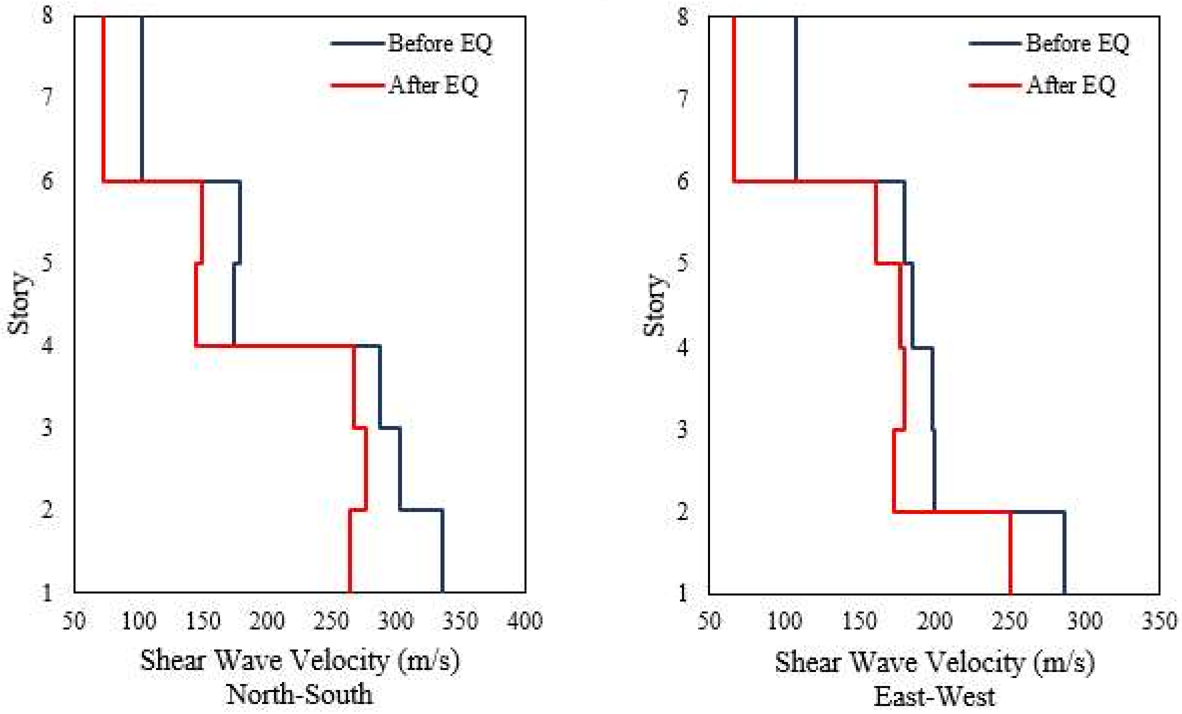


Fig. 4 – Shear wave velocity profiles computed before and after the earthquake. Both directions show damages identification and localization. SWVD has a maximum estimated reduction of 25%.

Fig. 5 enhances the validation of the technique through the correlation of shear wave velocity degradation and cracking patterns. For simplicity is only discussed the North-South orientation. On Fig. 5 is found that increment of the cracking in walls and columns increase as shear wave velocity degradation. From the 1st to the 4th floor, the cracking pattern declines (0.2 mm to 0.8 mm) as the SWVD in agreement. Moreover, from the 4th to the 6th floor, the SWVD increased as well as the cracking pattern (0.2 mm to 0.8 mm). However, at the 7th floor, SWVD decreased due to the reduction of cracking. The contribution of cracking patterns between 0.8 mm to 1.0 mm , and more than 1.0 mm seem unchanged the behavior of SWVD. Probably, it can be well explained by the low amount of crack length registered during the survey study in these categories. So, it is possible to infer that the excessive amount of cracking less than 0.2 mm does not significantly influence the reduction of shear wave velocity as well as the low amount of cracking registered for more than 0.8 mm. Nevertheless, the cracking range less than 0.2 mm seems to take over the SWVD at the 4th floor. Despite of the above mentioned, the general trend of SWVD appears to be strongly controlled by cracking patterns between 0.2 mm to 0.8 mm and the contribution of less than 0.2 mm at the 4th floor (black solid line, and grey dotted line, respectively).

After the 2011 Great East Japan Earthquake, the SRC-Annex BRI Building was repaired. Comprehending that fact, several month later were deployed a survey study to acquire data to evaluated if the repairing works have been effective. Fig. 6 shows the analysis after the restoring works on the North-South direction. The assessment was done only using four accelerometers. Thus, it is expected to obtain a less detailed shear wave velocity profile compared to Fig. 4. It is noticed that the repairing works were effective in recovering the stiffness dropped. It seems that even the building is stiffer than before the earthquake from the 2nd to the 8th floor.

Based on the information above presented, it is worthy to mention that the SHM using seismic interferometry is suitable technique to identify and localize damages in building by means of shear wave velocity profile, enhancing valuable information for decision making and disaster management.

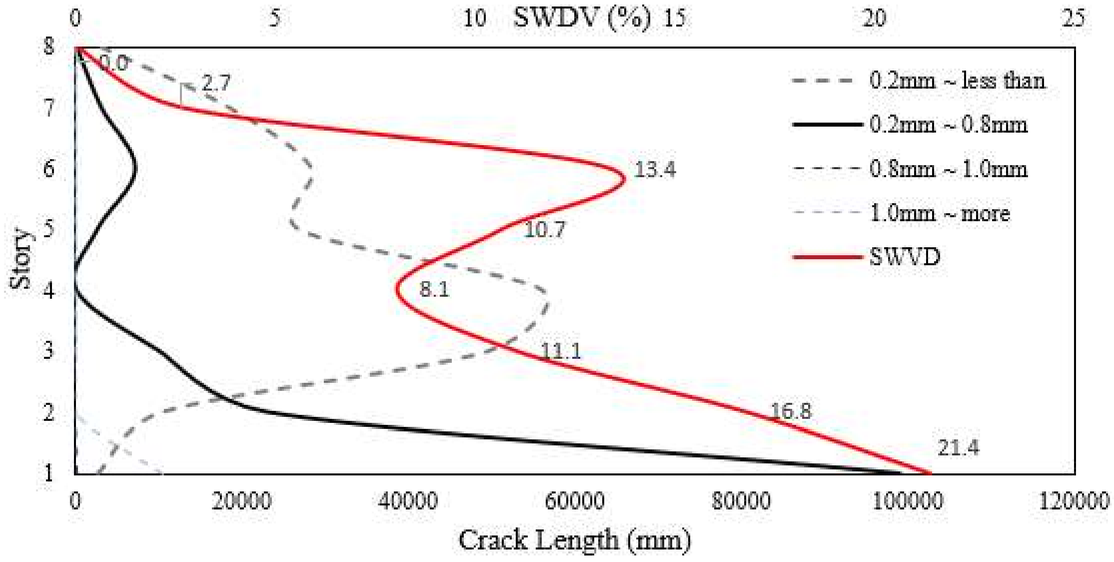


Fig. 5 – Correlation between SWVD and cracking pattern classification.

3.2 Case B: Steel-Sakishima Office

Case B has the task to reveal the effectiveness and usefulness of SI to straightforward estimate the shear stiffness by Eq. (6). The building is assessed considering the possible damages caused by the 2011 Great East Japan Earthquake. After the deconvolution is applied, the shear wave velocity is obtained. Then, shear stiffness is computed by Eq. (6). The shear stiffness calculated by SI is compared with that obtained by elastic design parameters.

Fig. 7 confirms the possibility to straightforward evaluate the shear stiffness from microtremor data through SI. The design stiffness is computed bases on elastic analysis information, and then averaged based on the sensor location to compared it with results from deconvolution. It is well recognized that from right side of Fig. 7 there is a substantial difference by 2 between design stiffness and computed ones. It is well explained due to the number of sensors used during the acquisition, suggesting increasing the number of sensor when the stiffness has large variability between stories owing to design criterion.

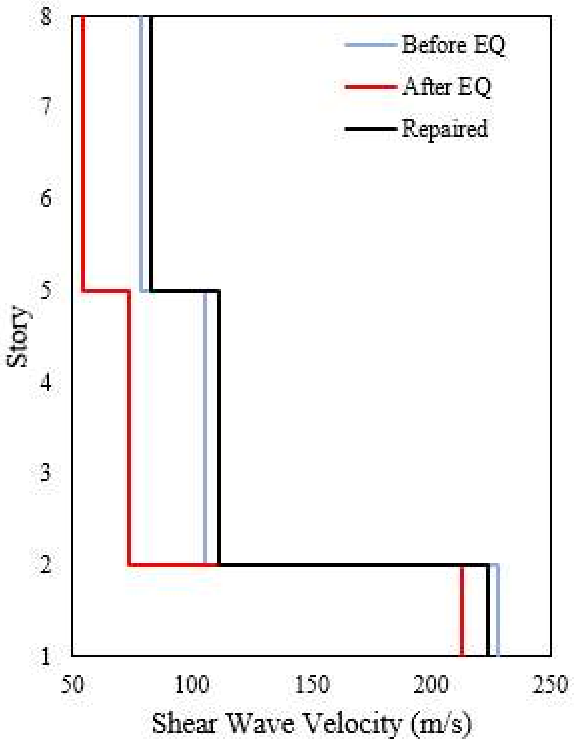


Fig. 6 – N-S Shear wave velocity profile of repairing works.

On the other hand, discussing the results before and after the earthquake, it seems that N229E direction suffered damages from the 1st to 18th floor and as of 38th to 52nd floor. However, if we consider the number of floors distributed among those stories, it is computed a maximum damages ratio of 5% per floor, which means that the building has not damages at all. This percentage could be addressed to some yielding points at beam-column locations. N319E shows a damages ratio of 0.3% accounting for undamaged direction. Therefore, the Steel-Sakishima Office is completely safe and can be operated after the event, no evacuation after the earthquake nor repairing, or retrofitting are needed.

3.3 Case C: Experimental Wooden 6F Building

Case C discusses the attempt to evaluate the sloshing effect on the building due to the temporary water pools using SI. Frequently, the fundamental period increases are associated to a growth of the building load, only if the building has not been damaged by an earthquake or a human event. Fig. 8 shows the deconvolution interferometry of North-South and East-West directions, black lines and red dotted lines refer to the behavior before and after the loads were added, respectively. EW reveals the expected rising of natural period by means of the dispersion patterns in the red dotted wave, increasing the wave traveling time, and reducing the shear wave velocity in Eq. (4). In the meantime, NS illustrates a decrement of the natural period through the red dotted wave that reduce the wave traveling time. In this case, the red dotted waves go within the reference black wave. This drop and growth in the parameter are specially called sloshing water effect. It was reported by [7] who studied the dynamic performance of the water into the tanks during the 1960 Chilean Earthquake, and it can explain the amplification and reduction of natural period in the building. However, further analysis should be implemented to grasp for a better performance characterization such as analysis of wave's shape changes, which is expressed as amplitude reduction and dispersion increment, both phenomenon well-known and associated to the attenuation factor.

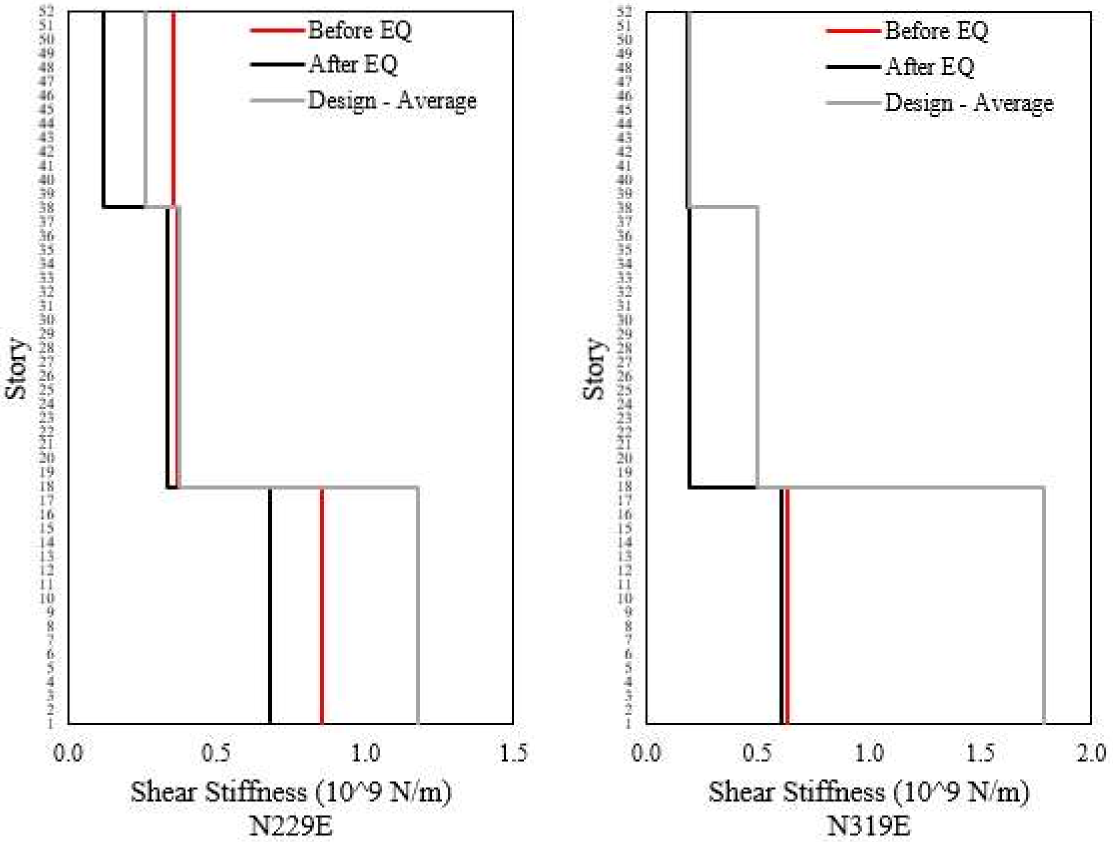


Fig. 7 – Shear stiffness of Steel-Sakishima Office estimated by Eq. (6) and compared with average-elastic design stiffness.

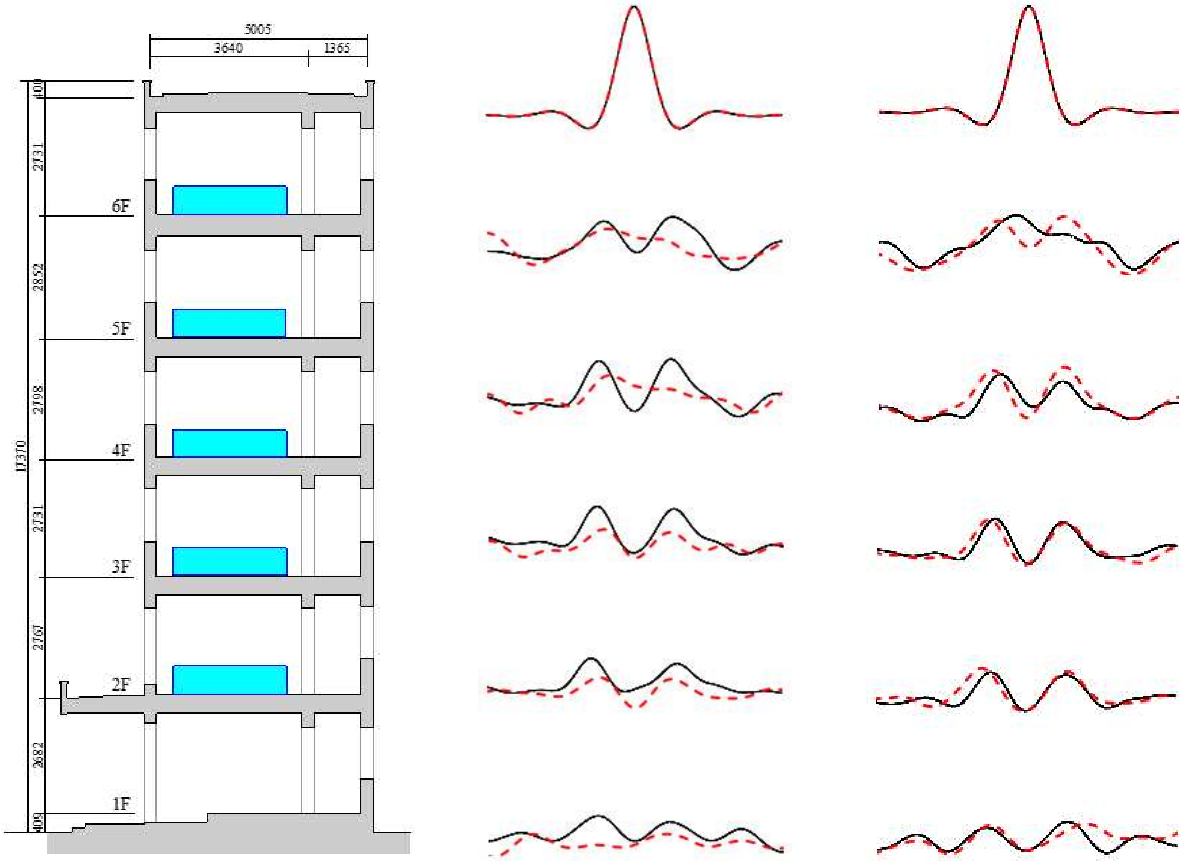
4. Conclusion

In this study has been demonstrated the versatility of Seismic Interferometry as tool for Health Monitoring of Building. We acknowledge its applicability and effectiveness on Steel Reinforcement Concrete, and Steel middle-rise and high-rise building to be used as system identification for damages detection and localization. Further analysis on masonry structures should be considered because most developing countries construct using bricks. Particularly, elevated social housing in Chilean territory.

Case A reveled the reliability, sensitivity and usefulness to detect damages by the shear wave velocity profile. Its validation by cracking patterns correlation demonstrated the tight relationship between cracks width and shear wave velocity degradation. However, the use of strong motion data for the analysis could address to an overestimation of dynamic parameters and underestimation of shear wave velocity leading to a false alarm related to damages evaluation. Therefore, it is recommended to analyze using ambient vibration or coda motions immediately after the earthquake to account for its uses as early warning system or introduce a correction factor to modify the shear wave velocity. For rehabilitation procedure ambient vibrations are well processed. We inferred that the overestimation of dynamics parameters could be associated to the opening and closing of cracks during the 2011 Great East Japan Earthquake.

Case B supports the straightforward and well-balance of the deconvolution interferometry to estimate shear stiffness by means of the approximation of Eq. (6). However, it has shown a high dependance on the number of sensors regarding drastic variations of stiffness per floor. Therefore, we advise the implementation of more sensor to grasp for improvements in the results for decision making related to repairing and retrofitting plans.

Case C indicted the possibility to assess sloshing effect employing seismic interferometry. The estimate results are coherent with those early discovered by [7]. Further efforts to analyze the attenuation factor through wave dispersion must be done. Furthermore, the damage detection, on wooden building, requires an extensive effort to decode the real behavior of shear wave velocity profile, most difficulties come from the wood anisotropy. Therefore, a probabilistic approach will be suitable to consider in additional examinations.



North-South East-West

Fig. 8 – Sloshing water effect on Experimental Wooden 6F Building.

5. Acknowledgement

We are deeply grateful for Building Research Institute (BRI) which belongs to Ministry of Land, Infrastructure, Transport and Tourism, and the International Institute of Seismology and Earthquake Engineering (IISEE) for their valuable contribution to carry out this research. The financial support of Japanese International Cooperation Agency (JICA) for funding this project under the Knowledge Co-Creation Program of Seismology, Earthquake Engineering and Tsunami Disaster Mitigation focused on developing countries.

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