Post-Earthquake Integrity Assessment of Multi-Story Buildings Using Layered Continuous Modeling with Seismic Recordings

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Abstract:

Traditionally, structural health monitoring algorithms are carried out by detecting changes in vibrational-based features related to global physical structure properties, which are not appropriate to identify minor and local changes along the structure height induced after earthquake events. Alternatively, exploring propagation features of seismic waves at designated levels at different time-windows during seismic excitation is potentially more sensitive to local changes. The damage-based wave signature indices are identified as the time elapse of waves traveling from one location to the other, resonance for waves propagating between damaged zones and building top, and change of wave amplitudes. This paper introduces a viable and efficient wave-based approach for assessing structural integrity condition by analyzing seismic response of the Millikan library building located in Pasadena, California due to the Yorba Linda earthquake of 2002. In particular, a hybrid model is first created for seismic wave motion in multistory buildings with unique structural features such as isolated massive floors and continuous inter-story columns/walls. The paper then explores the wave signature with the hybrid model that is sensitive to seismic damage and/or other aging/deterioration-related structural deficiency.

Keywords: Seismic responses in buildings, structural system identification, wave propagation-feature indices, seismic damage detection.

INTRODUCTION

An increasingly important task after being subjected to extreme damaging events— earthquakes and explosions—is to ensure public safety, rapid assessment of structural integrity, and the ability of the structure to continue serving its own purpose. Moreover, detecting structural damage at its earliest possible stages, especially for the existing old structures that were built without considering seismic resistance provisions, could be utilized to plan maintenance schedules and consider different feasible solutions to retrofit /replace damaged parts [1,2]. Therefore, examining building structures in real-time using proper structural monitoring system and effective damage detection algorithm is very important.

As a matter of fact, structural damage introduces changes into physical, geometrical, and mechanical properties of the structure, which adversely affect their current and future performance [3,4]. In fact, damage has no absolute meaningful measurement and thus, damage detection techniques depend upon comparing two different condition states of the structure; with the initial represents a healthy condition or un-damaged status. Therefore, an efficient and robust damage detection and identification technique is supposed to determine the occurrence, spatial distribution, and severity of damage [5,6].

Typically, damage detection schemes applied to civil structures are dependent on vibration-based approach (VBA) with discrete modeling. In this approach, damage detection is utilized by monitoring their dynamic parameters, or their derived quantities, which are extracted from system response and serve as damage indicators. However, VBA is limited in detect and quantify local changes in structural properties due to the fact that modal dynamic features are global in nature. Additionally, changes of modal features are influenced by environmental effects (temperature fluctuations) and boundary conditions (soil-foundation interaction). Furthermore, effectiveness of VBA in general, and recognition of local physical parameters change in particular, relies on availability of large number of seismic response recordings, which is not practical for most structures currently or in the near future.

An additional problem is that VBA has limitation so far in a comprehensive description of seismic motion in high rise buildings with a finite number of degrees of freedom (DOF) modeling in general, and distorting time-space representation of seismic motion in particular, and therefore, it captures major motion features as function of time and distorts and/or overlooks floor-to-floor motion relationship or wave propagation features.

On the other hand, modeling of seismic wave propagation through high rise buildings and exploring wave motion characteristics, as well as, identifying dynamic system parameters in terms of wave propagation features such as travel time and amplitude decay can in essence aid to help describe damage locality and severity.

Recent studies indeed show advantages of continuous-modeling over traditional discrete-modeling in some seismic response analysis and damage diagnosis of building structures. For example, [7] proposed to use 1D uniform shear-beam model for buildings and obtained seismic drift spectrum for design. [8] introduced 1D continuous/discrete modeling for structure-soil system with impulsive seismic excitation in bedrock. [9] modeled 2D anisotropic wave propagation for a real seven-story building [10] employed seismic interferometry (SI) to extract structural responses from seismic recordings. [11] studied seismic propagating waves in a 3D steel moment-frame building and verified with ETABS finite-element modeling.. [12] proposed a layered shear beam model for multistory RC building and presented algorithm for measuring wave travel time at different time-monitoring windows which helps detecting changes in structure, among others [13-16]. Building upon the aforementioned advances and others in relevant literature, this study uses recently-proposed 1D continuous-discrete modeling for modeling wave propagation in multistory building structures and examines response characterization and system identification and its application for post-earthquake structure health assessment.

METHODS:

MODELING OF SEISMIC WAVE MOTION IN MULTI-STORY BUILDINGS

In a piecewise continuous modeling, a multi-story building is modeled as a series of continuous shear-beam layers for inter-story columns/walls as shown in **Fig. 1**. Each floor level is characterized with shear wave speed $\boldsymbol{v} = \sqrt{\boldsymbol{G}/\boldsymbol{\rho}}\ (\mathbf{1} + \boldsymbol{i\gamma}\ \boldsymbol{sgn}(\boldsymbol{\omega}))$, cross-sectional area *A*, and hysteretic damping ratio γ, with story height *h*. Other parameters in this expression *G*, *ρ*, *i* and sgn($\boldsymbol{\omega}$) are, respectively, equivalent shear modulus, mass density, imaginary unit, and sign of frequency $\boldsymbol{\omega}$.

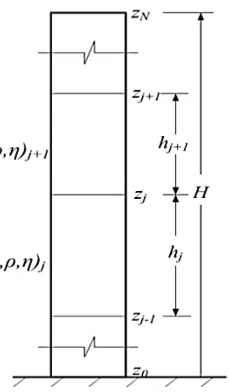


Figure 1: A piecewise-continuous model for an N-layer building subjected to seismic motion at z0

Shear displacements response of propagation of seismic waves at two locations *u(z,t)* and *u(z_r,t)* are, respectively, referred to as response location *z* (or $z_R=z-z_r$) and referenced location z_r, can be found

$$u(z,t) = \int_{-\infty}^{\infty} D_{Rr}(\omega) U_{z_r}(\omega) e^{i\omega t} d\omega = \int_{-\infty}^{\infty} d_{Rr}(t-\tau) u(z_r,\tau) d\tau \qquad (1)$$

where D_{Rr} and d_{Rr} are respectively, the displacement responses at *z*-level ($z=z_R$) to displacement impulse at z_r in the frequency and time domains, and U_{z_r} is the frequency counterpart of $u(z_r,t)$.

Equation 1 can also be interpreted as displacement response at *z* to a displacement input at z_r, which has the same mathematical form as the traditional, vibration representation of displacement response to an external force (e.g., Duhamel's or convolution integral), except the difference between force and motion inputs. Because of that, D_{Rr} and d_{Rr} are referred here to as wave-based or Generalized Frequency Response Function (GFRF) and Generalized Impulse Response Function (GIRF) respectively.

With the continuous piecewise model [16], a closed-form solution of GFRF, and subsequent GIRF with Fourier transformation of GFRF, can be found as

$$D_{Rr}(\omega) = \frac{U_{z_R}}{U_{z_r}} = \frac{(1+R_{NR})T_{Rr}}{(1-R_{rR}R_{NR})(1+R_{Nr})}$$
$$d_{Rr}(t) = \int_{-\infty}^{\infty} D_{Rr} e^{i\omega t} d\omega \qquad (2a,b)$$

In particular, model-based GFRF features can be expressed in terms of wave transmission and reflection coefficients, which are related to structural physical properties above the impulse referenced level as clearly demonstrated by Eq. 2a. One can be referred to [16] for more details on modeling wave motion in high-rise buildings using piecewise modeling.

STRUCTURAL SYSTEM IDENTIFICATION

In general, Structural System Identification (SSI) is the process of revealing dynamic system characteristics using seismic recordings—output response only—at real operation conditions. Matching seismic recordings with mathematical model will help to estimate model parameters which are related directly to dynamic structure characteristics, and thus to its physical properties. Furthermore, with the aid of Seismic Interferometry (SI), the influences of excitation source as well as soil-foundation system interactions could be eliminated and hence, a more reliable system identification is achieved [10]. For illustration, the Millikan library building is identified to reveal its dynamic properties in terms of wave-based features with a few seismic recordings after the Yorba Linda earthquake of September 3, 2002 using the piecewise continuous model.

The Robert A. Millikan Library is a reinforced concrete building with a basement and nine stories above the ground level, located on the campus of California institute of technology in Pasadena. The building is characterized with a total height of 43.90 m above the ground level and a 4.30 m basement level and the plan layout dimensions are 21x23 m. The lateral-resisting system is composed of moment-resisting frames and shear walls [17]. Figure 2 demonstrates the Millikan Library building, vertical cross-section in the north-south direction, and floor layouts.

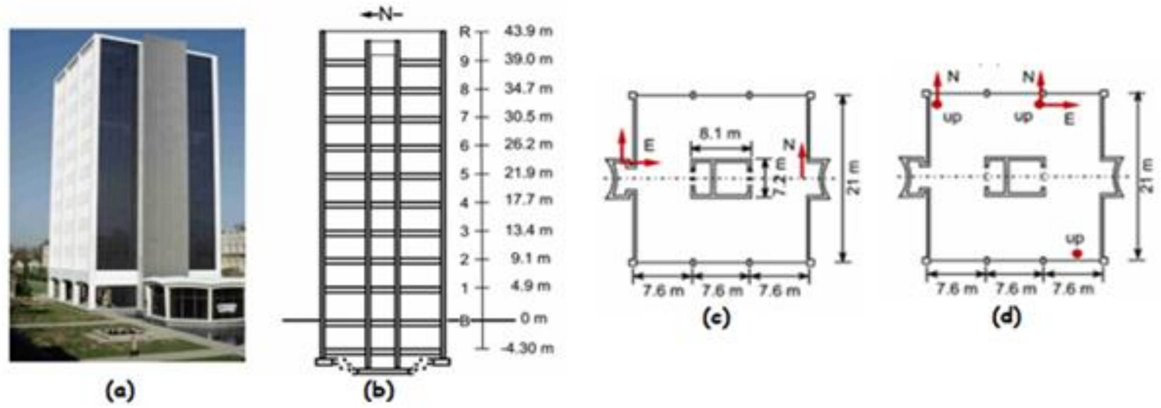
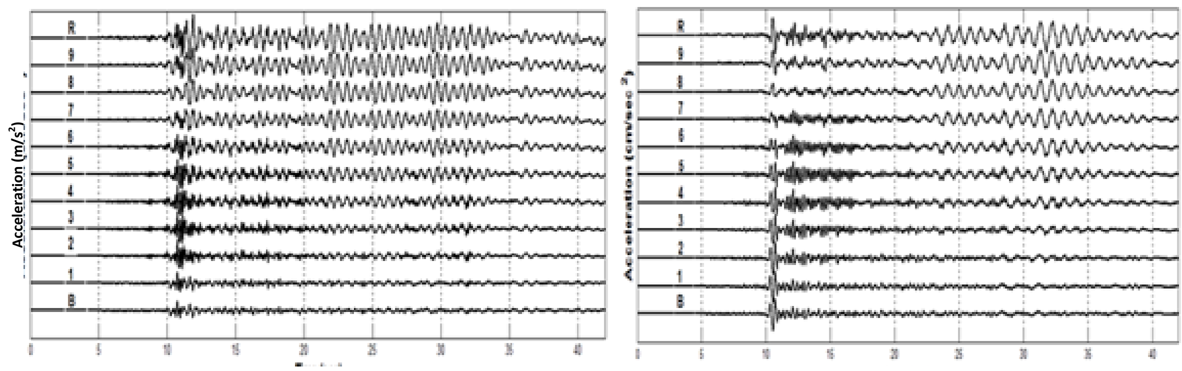


Figure 2: Millikan Library Building: a) Photo, b) vertical cross-section in the N-S direction, c) typical floor plan, d) basement floor plan [17]

In fact, the Millikan library is regarded as one of the most densely instrumented building in the U.S [17], where it is equipped with a dense network of accelerometers installed at every level. Note that in Fig. 2(c, d), the red dots show current location of sensors in the building at different floors. Response recordings of Yorba Linda, 2002 earthquake (M=4.8, R=40 km) in north-south and east-west directions are shown in Fig. 3.



a) North-South Direction

b) East-West Direction

Figure 3: Seismic Response Recordings of Yorba Linda Earthquake 2002 at Different Floors, a) North-South Direction, b) East-West Direction

In general, with a pair of seismic recordings at two locations, GFRF is obtainable as Fourier spectral ratio of the two recordings. One can first calculate the recording-based GFRF as

$$\tilde{D}_{j0} = \frac{\tilde{U}_j \tilde{U}_0^*}{|\tilde{U}_0|^2 + \varepsilon} \xrightarrow[\varepsilon \to 0]{} \frac{\tilde{U}_j}{\tilde{U}_0} \quad (3)$$

where $\tilde{U}$ is the seismic recordings in the frequency conjugate, and ε is a positive small number, implying the added white noise to avoid primarily unstable calculation of GFRF at some frequencies near the notches in the spectrum $|\tilde{U}_0|^2$. It should be noted that as ε approaches zero, $\tilde{D}_{j0}(\omega) \Rightarrow \tilde{U}_j / \tilde{U}_0$, which is the Fourier spectral ratio or the definition of GFRF in Eq. 2a. Note that the tilde over quantities *D* and *U* is used to distinguish the recording-based quantities from those based on modeling or Eq. 2a.

Figure 4 shows recording-based GIRF at selected floors with respect to a pulse motion response at the basement level at north-south and east-west directions. The figure reveals wave propagation features which are clearly exposed specifically in the floor-to-floor time shift and amplitude decay in (0-0.2 sec) time window.

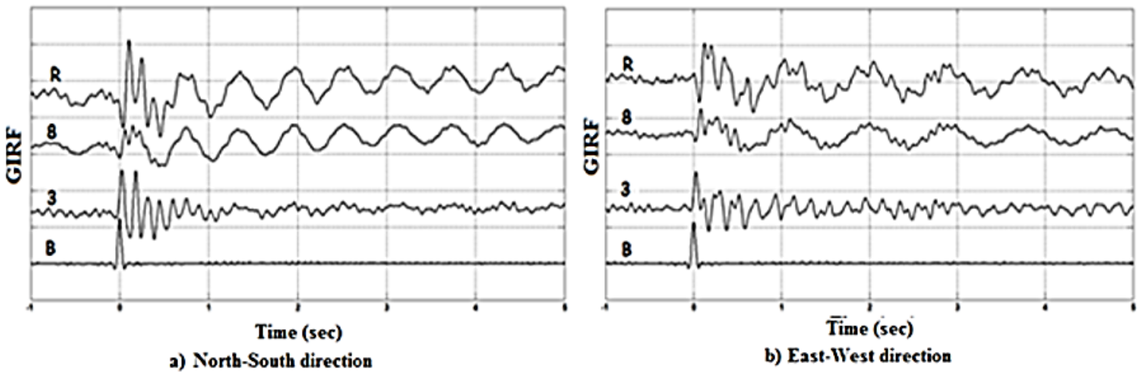


Figure 4: Recording-based GIRF at different floors due to impulsive acceleration response at the basement level: a) in the North-South direction, b) in the East-Wesat direction.

In particular, the first peak demonstrates the waves propagate upward with time shift depicts travel time between the considered floors whereas the second peak demonstrates the reflected wave by the roof propagates downward with even further time shift. Figures 4a,b show differences in arrival times and waveforms at the same floor level at both directions, which can be attributed to the different response of the building due to discrepancy in structural characteristics in both directions.

PARAMETRIC IDENTIFICATION WITH A TWO-LAYERED MODEL

Multistory buildings of medium-rise is very common to have consistent structural properties along its height. Therefore, one possible scenario is a two-layer model, which leads Eq. 2a to:

$$D_{R0}=\frac{\left(1+\alpha\left(e^{-2i\omega(\tau_1-\tau_z)}+e^{-2i\omega\tau_2}\right)e^{-2i\omega(\tau-\tau_z)}\right)e^{-i\omega\tau_z}}{1+\alpha\left(e^{-2i\omega\tau_1}+e^{-2i\omega\tau_2}\right)+e^{-2i\omega\tau}},\quad 0\le z\le h_1,\ \tau_z=\frac{z}{v_1} \tag{4}$$

$$D_{R0}=\frac{2\left(1+e^{-2i\omega(\tau-\tau_z)}\right)e^{-i\omega\tau_z}\Big/\left(1+r_{I_1}\right)}{1+\alpha\left(e^{-2i\omega\tau_1}+e^{-2i\omega\tau_2}\right)+e^{-2i\omega\tau}},\ h_1\le z\le h_1+h_2,\ \tau_z=\frac{h_1}{v_1}+\frac{z-h_1}{v_2} \tag{5}$$

where τ_z is the travel time for waves propagating from referenced level z_r to response location z_R, and

$$\alpha=\frac{1-r_{I_1}}{1+r_{I_1}},\ \tau_1=\frac{h_1}{v_1},\ \tau_2=\frac{h_2}{v_2},\ \tau=\tau_1+\tau_2 \qquad \text{(6a,b,c,d)}$$

The GIRF can be found by substituting GFRF of Eqs. (4,5) into Eq. (2b), where the integration can be obtained in closed form with the method of residues for some special cases and numerically for general cases.

With this approach in mind, one can apply SSI for Millikan Library building by fitting recording-based and 2-layer model-based GFRFs with a pair of recordings available at 8 floor and basement levels in the N-S direction as graphically demonstrated in Fig. 5. In principal, all the frequencies corresponding to the spectral peaks in Fig. 4 can be regarded as modal frequencies and then used for parametric identification. SSI is carried out here based on two identified modal frequencies, say ω_1=10.62 rad/sec and ω_2=14.21 rad/sec.

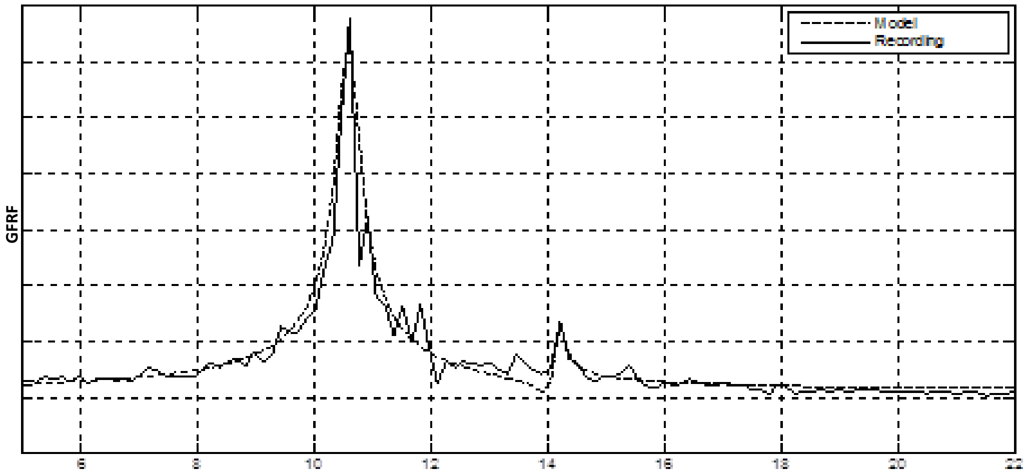


Figure 5: Recording-based and Model-based GFRFs at 8th Floor WRT Wave Motion at Basement Level.

In this study the stabilization parameter ϵ is estimated as 5% of spectral power of seismic recordings at referenced level and used primarily to avoid unstable calculations near the notches. GIRF is a powerful tool reveals arrival times of a pulse wave propagation generated by a virtual source at referenced level.

PARAMETRIC IDENTIFICATION WITH A THREE-LAYERED MODEL:

Increased number of layers in the model would be in principle more appropriate in realistically capturing the physical multi-story structure properties along the building height. To observe the influence of multi-layer model in system identification and a subsequently capturing wave propagation features, one can examine a three-layered shear beam model.

Specifically, parametric identification of the model characteristics is first carried out by matching two sets of the GFRF from recording and model based with a pair of seismic recordings at 8th floor and basement level for the N-S and E-W directions as shown, respectively, in figures 6 and 7. Note that the SSI is carried out here based on two identified modal frequencies, say ω_1=10.62 rad/sec and ω_2=14.21 rad/sec.

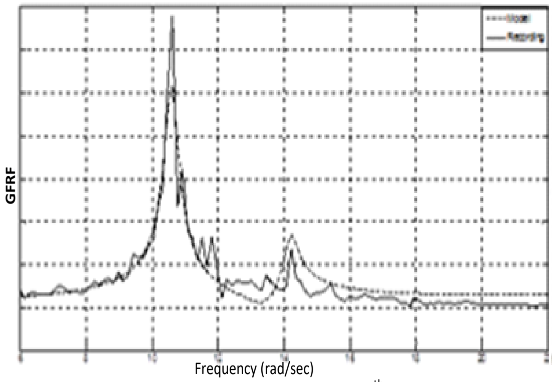


Figure 6: Recording and Model-based GFRFs at 8th floor WRT Wave Motion at Basement Level for the N-S Direction

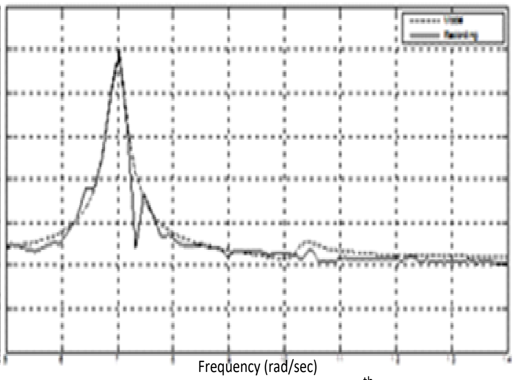


Figure 7: Recording and Model-based GFRFs at 8th floor WRT Wave Motion at Basement Level for the E-W Direction

The table below shows identified model parameters in the 2-layer and 3-layer models for the seismic response recorded in the N-S direction.

Table 1: Identified shear wave speeds and damping for different layered models

Model	ω_1 & ω_2 (rad/sec)	Wave speed and height	Damping
One-layer model from Zhang et al. 2011	10.77	v=330 m/s, h=48.20 m	0.0187
Two-layered model	10.77 14.21	v_1=345 m/s, h_1=47 m v_2=10 m/s, h_2=1.2 m	γ_1=0.03 γ_2=0.03
Three-layered model	10.77 14.21	v_1=331 m/s, h_1=22 m v_2=167 m/s, h_2=17 m v_3=22.5 m/s, h_3=8 m	γ_1=0.025 γ_2=0.020 γ_3=0.015

WAVE-BASED DAMAGE DETECTION SCHEME:

As a matter of fact, seismic damage has no absolute meaningful and it is best described as the relative measure of shear stiffness degradation of the building structure between two successive time windows in which the former represents the healthy case or the baseline state. In particular, the baseline state can be identified using the early part of seismic recordings where shear waves energy is low and hence minor structure response is established.

The scheme is based on analysis of model-based GIRF graphs and revealing pulse wave travel times between considered levels w.r.t referenced level and calculate shear wave velocity at successive time windows extracted from seismic recordings. Consequently, GIRF can be obtained numerically using the identified model parameters.

For instance, figures 8 and 9 graphically demonstrate model-based GIRF using the identified model parameters for recorded response at the N-S and E-W directions respectively.

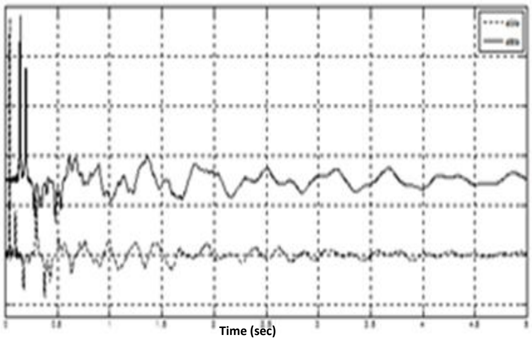


Figure 8: Model-based GIRF at 3rd and 8th Floors WRT Pulse Motion at Basement Level for the N-S Direction.

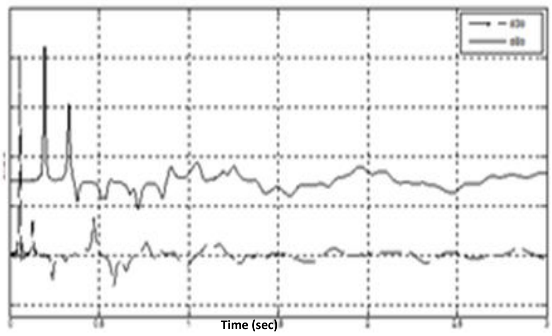


Figure 9: Model-based GIRF at 3rd and 8th Floors WRT Pulse Motion at Basement Level for the E-W Direction.

SUMMARY AND CONCLUSION

This study showed modeling and identifying of a full-scale RC building with a few seismic recordings with the aid of generalized frequency response and impulse response functions. In particular, the building is modeled as layered-shear beams with fixed-base, where every layer corresponds to one or more building's floors. Especially, a wave-based damage detection algorithm is developed, in which arrival pulse wave times at considered levels inside the model is captured and analyzed at sequent intervals of seismic recordings. With this in mind, other wave propagation features can be estimated and compared to infer localized damage occurrence, exemplified as amplitude decay and inter-story drifting as well as wave polarity.

This method is characterized simpler and directness and requires only a few of recordings. which can be used to improve greatly the efficiency of post-earthquake structural condition assessment. Reduce occurrence of false warning and consequences of functioning interruptions especially in-service buildings –hospitals and residential buildings.

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