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PWCPI-based procedure to estimate capacity curve for instrumented high-rise buildings

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ABSTRACT

Capacity curve estimated from seismic floor accelerations can provide an informative description of the structural behavior soon after an earthquake. Detailed information on instrumented buildings is not always available. Therefore, this paper proposes a strategy based on the piece-wise cubic polynomial interpolation (PWCPI) procedure to estimate the capacity curve for high-rise buildings from accelerations using limited sensors placed at regular intervals along the height of the building. The validity of the method is assessed by numerical simulations and shaking table tests.

1 INTRODUCTION

Rapid development in sensor technologies has made it possible to use measured data from buildings and infrastructures to diagnose the condition of a structure, which allow for a rapid and reliable evaluation on structural damage condition soon after an earthquake. Several vibration-based methods have been developed for damage evaluation in recent decades (Moaveni B 2007), such as methods based on the change of modal parameters, methods based on tracking the hysteretic behaviors of the structures, and methods based on modal strain energy.

The capacity spectrum method (CSM) firstly proposed by Freeman (Freeman 1998), has been served as an efficient tool for seismic design and assessment. The capacity curve is considered to be the fundamental-mode relationship between mass-normalized roof displacement and base shear, providing a straightforward and informative description of the structural behaviour immediately after an earthquake. Early successful in situ applications can be found in (Iemura 1974) and an automatic procedure based on wavelet transform for deriving structural capacity curve from its earthquake acceleration response has been developed (Kusunoki 2017) (Pan and Kusunoki 2018) recently.

The availability and quality of the recorded data play an important role in the accuracy of the estimated capacity curve. Generally, the more sensors placed on the building, the more accurate capacity curve could be obtained. However, in real applications, issues may arise for sensors installation for high rise buildings, where the number of sensors is limited by budgets and accessibility. Therefore, issues related to optimal sensor placement (OSP) on structures have received much attention in the recent years (Yi 2011) (Yi 2012). However, most OSP methods require model properties, such as stiffness and mass distribution of structures, which are difficult to obtain in most cases. Meanwhile, as buildings are normally instrumented with a limited number of sensors on the floor, the motions of the remaining floors are estimated by an interpolation procedure. Normally, the process is conducted by a piece-wise cubic polynomial interpolation (PWCPI) procedure (Limongelli 2003) or a mode-based interpolation (MBI) procedure (Goel 2008). Although these response reconstruction approaches work well in the linear-elastic range, their accuracies in the nonlinear range have not been verified. Another issue related to interpolation is the selection of appropriate locations for sensor installation.

Therefore, in this paper, a strategy to estimate capacity curve with a limited number of sensors for high-rise buildings based on the PWCPI procedure is proposed. One salient merit of PWCPI is that the interpolation procedure does not require the modal properties of the building. Meanwhile, sensors are instrumented on floors at a regular interval along the height of the building; thus, detailed structural information is not necessary for the optimization of the sensor location. Numerical simulations and shaking table tests are conducted to illustrate the method.

2 METHODOLOGY

The capacity curve commonly obtained by the pushover analysis is the relationship between base shear force, V_b, and the roof (*N*-th floor) displacement, x_N, of the structure. To directly compare with the demand response spectra, V_b and x_N are converted to a spectral set of coordinates S_a and S_d using the dynamic characteristics of the fundamental mode to represent the structure as a single-degree-of freedom system. Using the measured structural response $\ddot{x}_i$ for each floor, mass-normalized ${}_1\tilde{S}_\mathrm{a}$ and ${}_1\tilde{S}_\mathrm{d}$ are given by

$$ {}_1\tilde{S}_\mathrm{a} = \frac{\sum_{i=1}^{N} m_i \, {}_1\{\ddot{x}_i\}}{{}_1\bar{M}} \tag{1} $$

$$ {}_1\tilde{S}_\mathrm{d} = \frac{{}_1\{x_\mathrm{N}\}}{\beta_1 \cdot {}_1u_\mathrm{N}} \tag{2} $$

where ${}_1\{\}$ denotes the extraction of the fundamental-mode component from the response, ${}_1u_\mathrm{N}$ is the *N*-th floor element of the fundamental mode $\{{}_1u\}$, β_1 is the fundamental-mode participation factor $= \dfrac{\sum_{i=1}^{N} m_i \cdot {}_1u_i}{\sum_{i=1}^{N} m_i \cdot {}_1u_i^2}$ (m_i = lumped mass on the *i*-th floor), and ${}_1\bar{M}$ is the equivalent mass for the fundamental mode $= \dfrac{(\sum_{i=1}^{N} m_i \cdot {}_1u_i)^2}{\sum_{i=1}^{N} m_i \cdot {}_1u_i^2}$. In practice, the fundamental mode and equivalent mass can be estimated from floor accelerations and relative mass ratio.

To isolate the fundamental-mode component from the response, a wavelet transform method (WTM) is utilized:

$$_1\{\ddot{x}_i\} = \sum_j \ddot{x}^{\mathrm{W}}_{i,j} \tag{3}$$

$$_1\{x_{\mathrm{N}}\} = \sum_j x^{\mathrm{W}}_{\mathrm{N},j} \tag{4}$$

where $\ddot{x}^{\mathrm{W}}_{i,j}$ is the *j*-th ranked component of measured acceleration at the *i*-th floor obtained through WTM, and the terms $\sum_j \ddot{x}^{\mathrm{W}}_{i,j}$ and $\sum_j x^{\mathrm{W}}_{\mathrm{N},j}$ are the sum of responses at several ranks to approximate the fundamental-mode component of $\ddot{x}_i$ and x_{N}, respectively. It is possible to select the fundamental-mode component automatically and estimate the capacity curve in a short time.

The strategy to estimate capacity curve with a limited number of sensors can be divided into two steps. First, the accelerations of noninstrumented floors are calculated by interpolating the accelerations at floors at a regular interval along the height of the building based on the PWCPI procedure. It is useful to emphasize that the accelerations at the base and roof of the building are always included in the interpolation. Next, the capacity curve is estimated from the accelerations at each floor using the wavelet-based method.

3 NUMERICAL SIMULATION

In this section, the responses of shear buildings with 8, 18, and 28 stories subjected to seismic ground motion are used to explore the accuracy of estimated capacity curve with different number of sensors placed at regular intervals along the height of the building.

Each building was assumed to have a uniform floor mass of 200 tons. Trilinear model was used to idealize the nonlinear behavior of each story, and initial stiffness decreased with the floor height in accordance with the Japanese code. The fundamental mode frequencies of the three building models were 1.639 Hz, 0.874 Hz, and 0.567 Hz, respectively. The damping was defined as classical damping with damping ratios in the fundamental and second modes to be 5%.

In this study, the accelerations at each floor were simulated by the time history analysis (THA) of building models subjected to ground motions at the base of the buildings. The motions used in the investigation are translations recorded during the 1940 Imperial Valley earthquake, 1994 Northridge earthquake, and 1995 Kobe earthquake. The THA accelerations at limited floors were used to interpolate accelerations at the remaining floors. Next, the capacity curve was estimated from accelerations at all floors. The accuracy of the interpolation procedure was evaluated by comparing the capacity curve from responses at all floors with that from the PWCPI procedure using responses interpolated at limited floors.

The accuracy of the estimated capacity curve from the PWCPI procedure is defined by function of fitness F as follows:

$$F = \frac{\dfrac{S^{\mathrm{Inp}}_{\mathrm{disp.Pos}}}{S_{\mathrm{disp.Pos}}} + \dfrac{S^{\mathrm{Inp}}_{\mathrm{disp.Neg}}}{S_{\mathrm{disp.Neg}}} + \dfrac{S^{\mathrm{Inp}}_{\mathrm{acc.Pos}}}{S_{\mathrm{acc.Pos}}} + \dfrac{S^{\mathrm{Inp}}_{\mathrm{acc.Neg}}}{S_{\mathrm{acc.Neg}}}}{4} \tag{6}$$

where $S_{\text{disp.Pos}}$ and $S_{\text{disp.Neg}}$ are the maximum spectral displacements of the capacity curve estimated from responses at all floors without interpolation in the positive and negative directions, respectively; $S_{\text{acc.Pos}}$ and $S_{\text{acc.Neg}}$ are the corresponding spectral accelerations; $S_{\text{acc.Pos}}^{\text{Inp}}$ and $S_{\text{acc.Neg}}^{\text{Inp}}$, and $S_{\text{disp.Pos}}^{\text{Inp}}$ and $S_{\text{disp.Neg}}^{\text{Inp}}$ are the corresponding spectral acceleration and spectral displacement estimated from responses through interpolation, respectively. The capacity curve is estimated with high quality when F is close to unity.

Each input motion was scaled to different levels of peak ground acceleration so that the building models could deform from the linear-elastic range to the nonlinear range. The trend of accuracy of the PWCPI procedure with different number of sensors was plotted with respect to the maximum inter-story drift angle, as shown in Figures 3–5. Note that as the soft-story condition may occur in the lower floors, resulting in stiffness discontinuity, at least one additional instrument was needed somewhere in the middle floors, apart from the ground floor and the roof. Therefore, at least three sensors were required during the interpolation process.

When the building models deformed within the elastic range (maximum inter-story angle < 1/1000 rad), F was very close to unity, indicating that the estimated capacity curves from the PWCPI procedure matched well with those from responses at all floors without interpolation. Figure 1(a) shows the capacity curve of 18-story building estimated from accelerations using PWCPI with three sensors and capacity curve without interpolation during the Northridge earthquake. It is found that these two capacity curves agree well. The predominant frequency from the capacity curve using PWCPI was 0.87 Hz, which is consistent with the design value. A nonlinear case with three sensors during the Kobe earthquake is also presented in Figure 1(b), showing good consistency between the estimated capacity curve with all sensors and limited sensors.

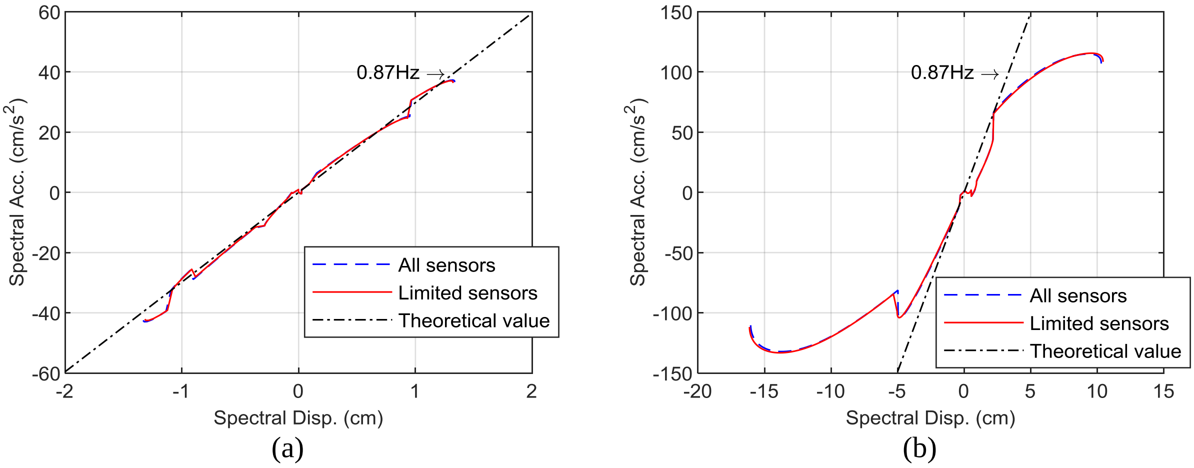
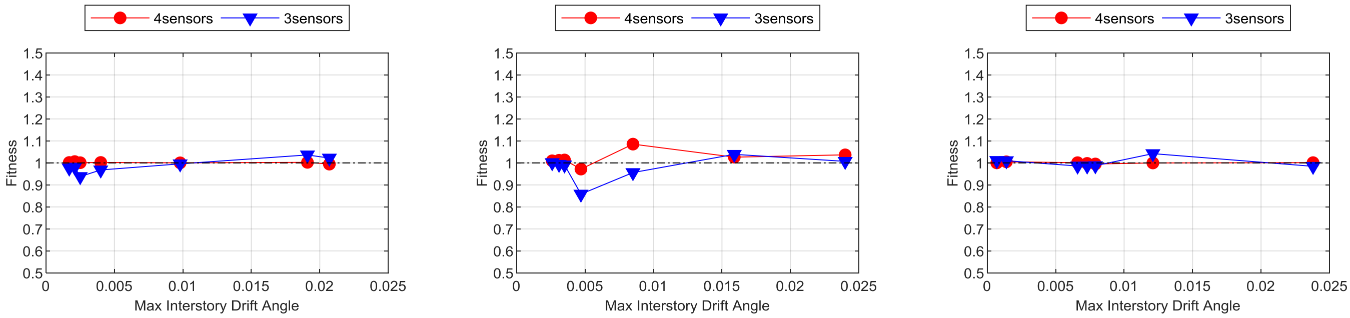


Figure 1: Comparison of capacity curve from THA and PWCPI: (a) linear case; (b) nonlinear case

The results presented in Figures 2–4 indicate that the accuracy was improved with increased sensors and that the accuracy was high even in a large deformation range. For the eight-story building, although there were some small fluctuations during the Kobe earthquake, F was close to unity in most cases using three sensors. Some scatters were found for the 18-story building with three sensors, which shows that three sensors cannot be used to reconstruct the response and at least four sensors are necessary for the 18-story building. Four sensors are suitable for 28-story building and using more sensors could improve the accuracy. Table 1 summarizes the minimum number of instrumented sensors.



(a) (b) (c)

Figure 2: Accuracy of PWCPI for eight-story building during the (a) 1940 Imperial Valley earthquake, (b) 1995 Kobe earthquake, and (c) 1994 Northridge earthquake

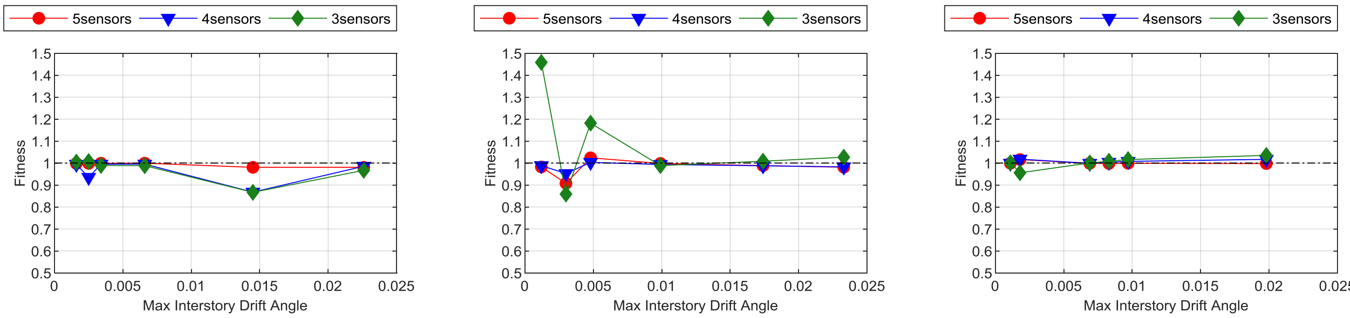


Figure 3: Accuracy of PWCPI for 18-story building during the (a) 1940 Imperial Valley earthquake, (b) 1995 Kobe earthquake, and (c) 1994 Northridge earthquake

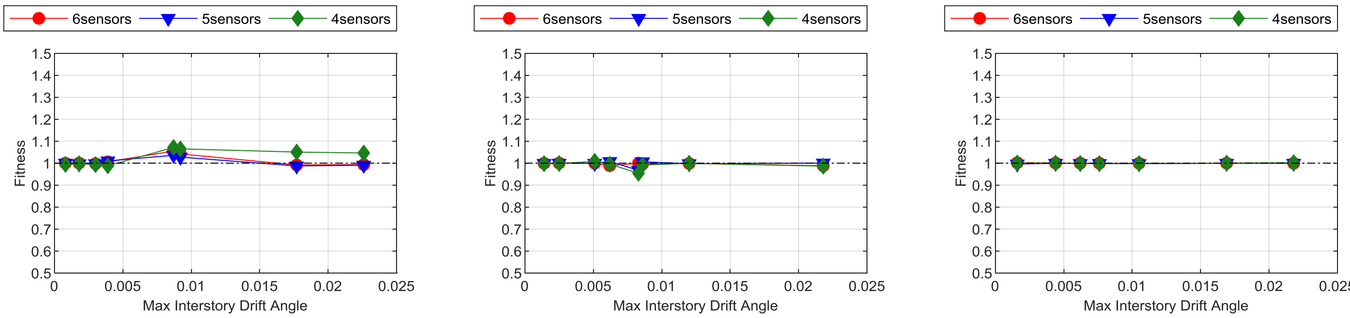


Figure 4: Accuracy of PWCPI for 28-story building during the (a) 1940 Imperial Valley earthquake, (b) 1995 Kobe earthquake, and (c) 1994 Northridge earthquake

Table 2: Required numbers of sensors

	8-story	**18-story**	**28-story**
Minimum numbers	3	4	4

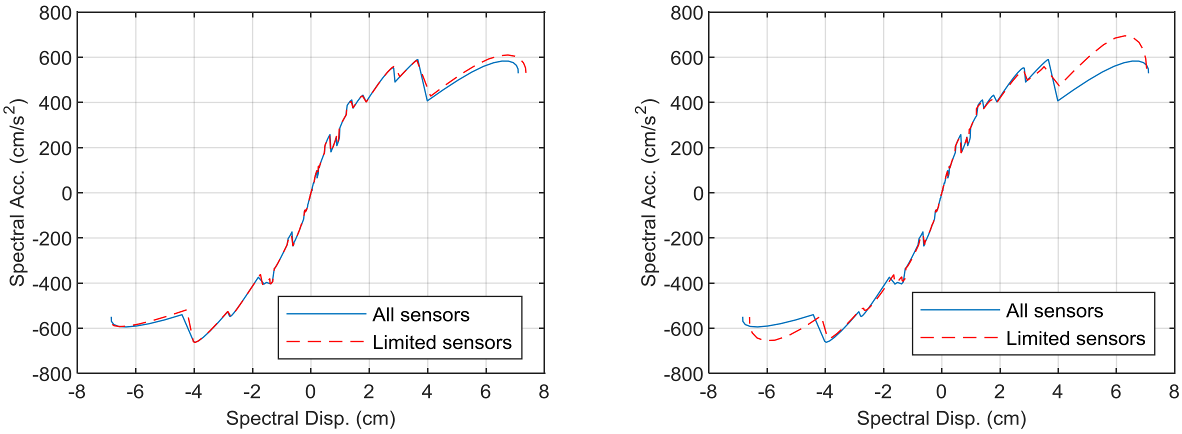
4 SIX STORY RC WALL FRAME SHAKING TABLE TESTS

The test specimen consisted of 3 paralleled three-bay in the longitudinal (Y) direction and two bays in the transverse (X) direction. The span widths were 5 m in the longitudinal and transverse direction. The plan dimensions were 15m by 10m, and the height of the structure was 15m. The central frame had a structural wall in the central bay continuously from the 1st to the 6th story (see Figure 5).

The model was tested on the tri-axial shaking table E-defense (size: 20m×15m) by exerting series of earthquake waves. The input motion was the horizontal components (East-west and North-south) and the vertical (Up-down) component of the 1995 Hyogo-ken Nambu earthquake recorded at the Japan Meteorological Agency. All three components were applied simultaneously. To induce progressive damage of the structure, the specimen was subjected to a series of scaled earthquake loads during the tests. The specimen finally collapsed due to shear failure in short columns and the structural wall at the 1st-story during the last strong earthquake motion.

Figure 5: Six-story RC shear wall building test model

Figure 6 (a) shows the capacity curve estimated through the PWCPI procedure with three sensors installed at the ground floor, fourth floor, and the roof. Nonlinear behavior is well displayed in the figure. It can be shown that the capacity curve using the PWCPI procedure with three sensors and that using data from all floors was consistent. For comparison, the capacity curve estimated using PWCPI with two sensors (ground floor and roof) is also shown in Figure 6 (b). These two curves matched well in the linear region, but some differences were found in the nonlinear region. Figure 7 (a) and Figure 7 (b) show the height-wise distribution of the fundamental-mode accelerations at the peak spectral acceleration point using the PWCPI procedure with three and two sensors, respectively. As shown in the figure, the height-rise distribution with three sensors approximates well with that using all sensors. Meanwhile, the error caused by using two sensors is large for the middle floors when one of the floors is ignored in the interpolation procedure and tends to be smaller for the upper and lower floors. The large error in floor accelerations results in a poor approximation of capacity curve. This implies that two sensors cannot be used to reconstruct an accurate capacity curve when the structure behaves nonlinearly. Therefore, at least three sensors are necessary in a six-story building.



(a) (b)

Figure 6: Capacity curve of six-story building: (a) three sensors; (b) two sensors

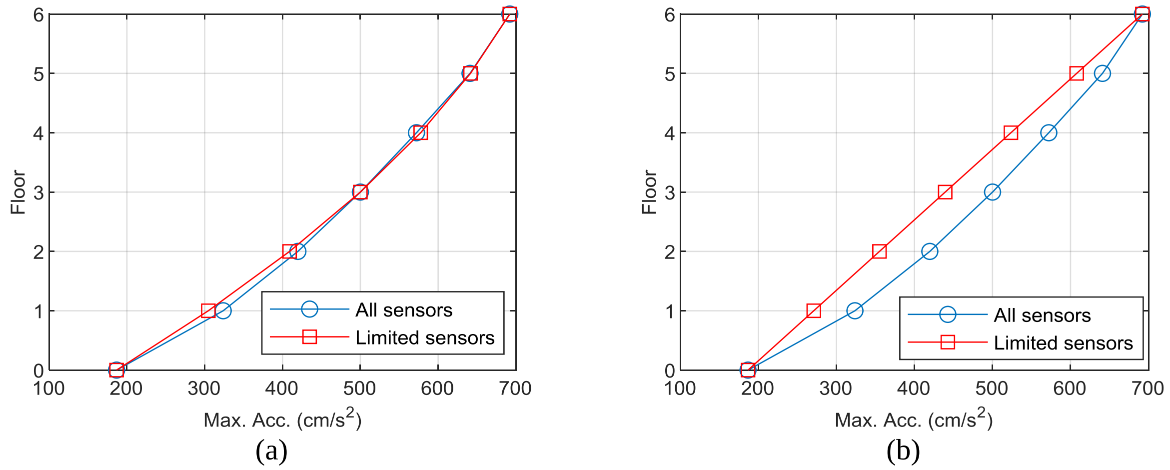


Figure 7: Height-wise distribution of maximum acceleration using the PWCPI procedure: (a) three sensors; (b) two sensors

5 CONCLUSIONS

The strategy for capacity curve estimation from accelerations at limited floors is proposed in this study. Numerical simulations and shaking table tests have shown that the estimations based on the PWCPI procedure using data from sensors placed at regular intervals provide good estimates at the linear-elastic range as well as the nonlinear range. The entire procedure does not require sensors to be installed at optimal locations calculated from the modal property. This finding is useful and convenient in practice, because modal property, such as mode shape, is not always available for the instrumented building. The required number of sensors is also provided in this study.

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