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Cost-effective Smart Sensing Technologies to Monitor the Residential Building Systems

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Abstract

To monitor the aseismic performance of wooden houses, several methods have been examined for detecting damage by measuring changes in dynamic characteristics such as the natural periods of buildings before and after an earthquake. In addition, a method has been proposed to estimate the damage accurately by calculating the maximum deformation amount at the earthquake, based on data obtained from strong-motion seismographs installed in the buildings.

In this research, the authors verify the performance of a developed building damage monitoring system, consisting of inexpensive LAN strong-motion seismographs, smartphones, and seismic electric breakers connected via a LAN network, based on acceleration records during the E-Defense wooden houses experiment. The LAN strong-motion seismographs used an Ethernet cable for data communication and power supply (PoE). In the experiment, the LAN strong-motion seismographs were installed on each floor of two three-story wooden houses (P&B type and lightweight shear-wall type). These LAN strong-motion seismographs were time-synchronized with the server on the network via SNTP, allowing us to obtain 100 Hz sampling acceleration records from multiple locations. In the experiment, the maximum story drift angle of the wooden houses during vibration was identified by calculating the deformation amount at each measurement location from the integral of the acceleration history acquired by the LAN strong-motion seismographs.

Although mobile devices such as smartphones were used to perform time correction by NTP, full synchronization between multipoint recordings cannot be realised with 100 Hz sampling data. This research aimed to achieve monitoring of building damage caused by vibration with a single smartphone or seismic electric breaker on the floor (or in the vicinity) of second story at the wooden house. In this paper, the authors proposed a procedure for building damage monitoring using seismometer devices that do not guarantee time synchronization. The proposed method estimates the first floor behavior using only the response acceleration record from the second floor, based on an inverse response analysis in the frequency domain of the equivalent single-DOF system considering the plastic deformation behavior. The evaluation accuracy of the proposed method is inferior to that using a multi-device (e.g. using LAN strong-motion seismographs that guarantee time synchronization). However, the proposed method mostly corresponds to the E-defense experiment results, and the accuracy of the proposed method is within tolerance.

Keywords: Structural Health Monitoring, Wooden House, Time Synchronization, Smartphone, Seismic Electric Breaker

1. Introduction

The 1995 Kobe earthquake [1] and the 2011 Tohoku earthquake [2] caused catastrophic consequences to many wooden houses. A quick damage evaluation of houses in a disaster-stricken area is important to minimize confusion after an earthquake. In recent years, several methods to monitor the aseismic performance of wooden houses have been examined, aiming at detecting damage by measuring changes in dynamic characteristics such as the natural periods of buildings before and after an earthquake [3, 4]. In addition, a method has been proposed to estimate the damage accurately by calculating a maximum deformation amount at the earthquake, based on data obtained from strong-motion seismographs installed in the buildings [5, 6].

In this paper, the authors verify the performance of a developed building damage monitoring system, consisting of inexpensive LAN strong-motion seismographs, smartphones, and seismic electric breakers connected via a LAN network, based on acceleration records from the E-Defense wooden houses experiment. The LAN strong-motion seismographs were time synchronized with the server on the network via SNTP, allowing us to obtain 100 Hz sampling acceleration records from multiple locations. In the experiment, the maximum story drift angle of the wooden houses during vibration was identified by calculating the deformation amount at each measurement location from the integral of the acceleration history, acquired by the LAN strong-motion seismographs.

In contrast, although mobile devices such as smartphones can perform time correction by NTP, full synchronization between multipoint recordings cannot be expected using 100 Hz sampling data. In this paper a procedure for building damage monitoring using seismometer devices that does not guarantee time synchronization is proposed.

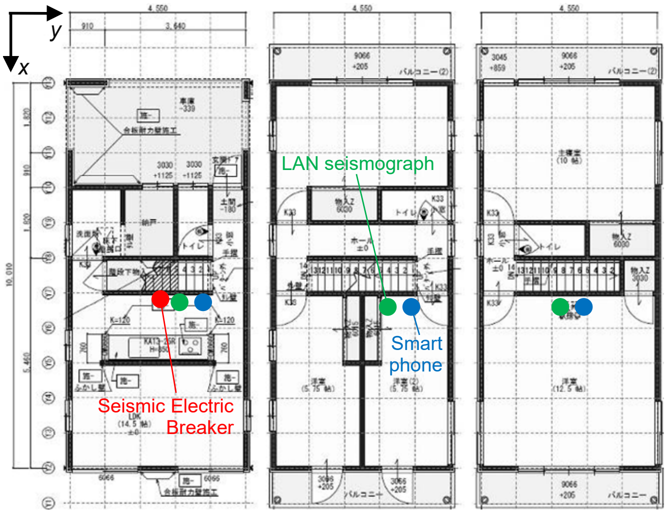
2. E-Defense Shaking Table Test

2.1 Specimen

Two 3-story wooden houses were used for the test (see Figure 1), an adopted a Post and Beam (P&B) structure, and a Shear-Wall (SW) structure. This paper only discusses the P&B specimen. Figure 2 shows a plan view of each floor.

As shown in Figure 2, LAN strong-motion seismographs, smartphones, and seismic electric breaker were installed in the house. The smartphones and LAN seismographs were placed on the floor of 1st to 3rd stories (see Figure 3). A breaker with MEMS accelerometer was attached to the wall near the ceiling on the 1st story (see Figure 4). The LAN strong-motion seismographs use an Ethernet cable for data communication and power supply (PoE).

Fig. 1 – Test specimens were 3-story wooden houses.



(a) 1st Floor (b) 2nd Floor (c) 3rd Floor

Fig. 2 – Plan view of specimen.

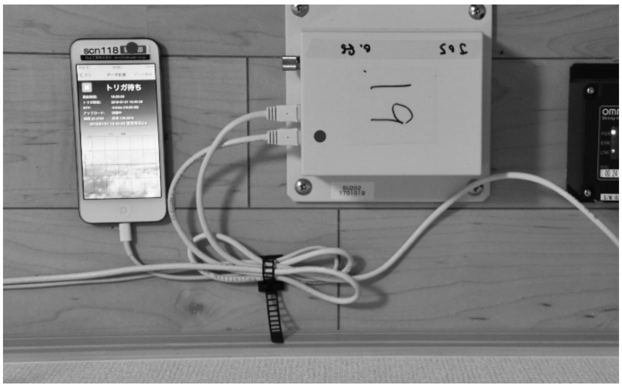


Fig. 3 – LAN seismograph and Smartphone.

Fig. 4 – Seismic Electric Breaker of 1st story.

2.2 Input waves

The shaking table test was programmed to impose gradually progressive damage to the wooden house using main input waves of gradually increasing amplitude. A total of three JMA Kobe waves (see Figure 5) of different amplitudes and one JR Takatori wave (see Figure 6) were inputted in February 7, 2019. The maximum horizontal acceleration of each main excitation ranged between 1.9 m/s^2 to 14.3 m/s^2. Table 1 shows the maximum acceleration for each excitation.

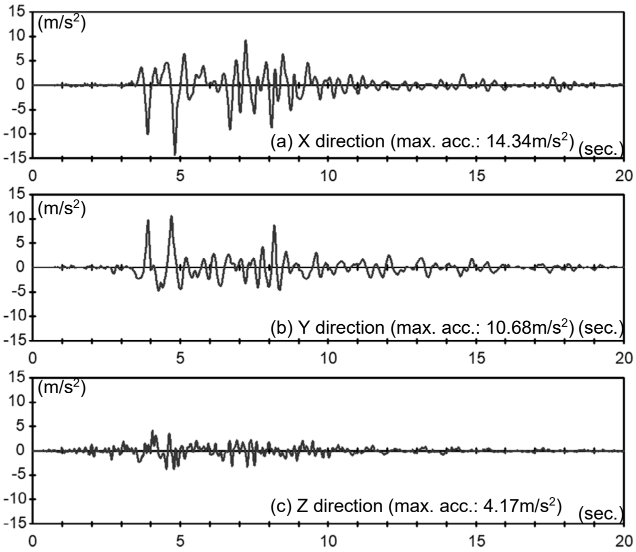


Fig. 5 – JMA Kobe Wave 100% (Excitation 3).

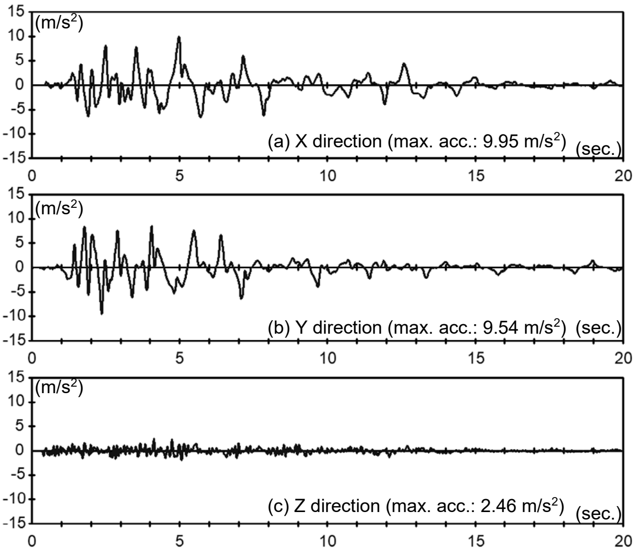


Fig. 6 – JR Takatori Wave 100%. (Excitation 4).

Table 1 – Maximum acceleration and response deformation for each excitation of February 1, 2019.

Excitation Number	Input Wave	Maximum Acceleration (m/s^2)			Maximum Story Drift Angle (1st story)	
		X dir.	Y dir.	Z dir.	X dir.	Y dir.
1	JMA Kobe 25%	2.22	1.90	0.78	1 / 769	1 / 526
2	JMA Kobe 50%	5.06	4.28	1.82	1 / 145	1 / 128
3	JMA Kobe 100%	14.34	10.68	4.17	1 / 27	1 / 49
4	JR Takatori 100%	9.95	9.54	2.46	1 / 19	1 / 36

2.3 Damage to wooden house

In Table 1, the maximum story drift angle (SDA) of the test specimen (1st story) during main excitation is shown. In excitation 2 (JMA Kobe 25%), the maximum story drift angle was 1/500 or less, indicating an elastic behaviour. In excitation 4 (JMA Kobe 50%), the maximum story drift angle exceeded 1/150. The interior wall cloths were cracked, and the specimen was partially plasticized. In excitation 6 and 8 (JMA Kobe 100% and JR Takatori 100%), the maximum story drift angle exceeded 1/50, and significant damage occurred.

3. Performance evaluation of the Smartphone and Seismic Electric Breaker

Figure 7 shows the floor response acceleration time histories of Excitation 3 (JMA Kobe 100%). Green lines show the LAN strong-motion seismograph records at the floor of the 2nd story. Blue and red lines are responses obtained from the smartphone and the seismic electric breaker. The smartphone's and the LAN seismograph's records have almost the same time histories. The breaker record contains high frequency components. This is because the breaker was attached to a non-structural wall. However, the breaker record approximately matches those from the LAN seismograph.

The above results show that smartphones and seismic electric breakers have the potential to be used to monitor damage in wooden houses. In particular, the breaker attached to the non-structural wall near the ceiling of the first story was almost equal to the response acceleration of the floor of the second story.

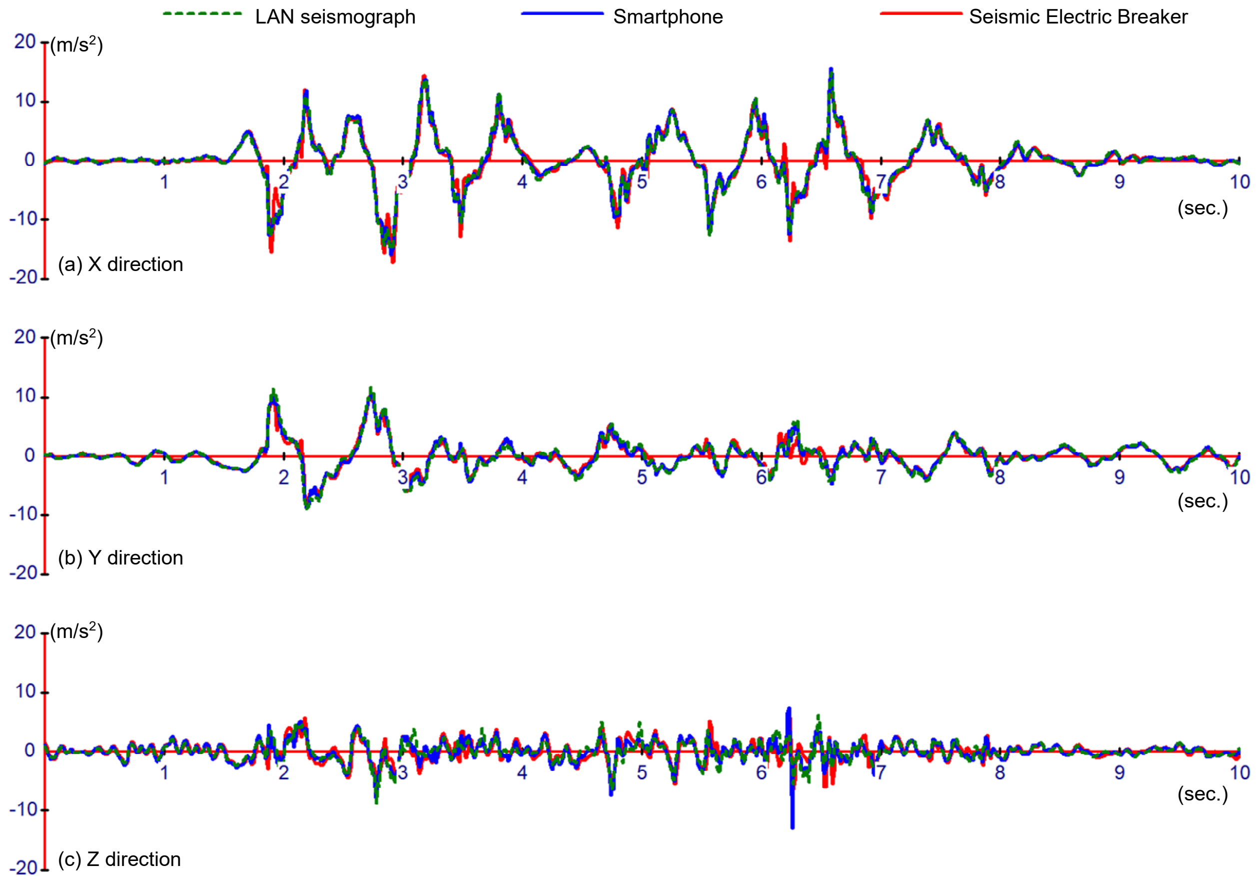


Fig. 7 – 2nd floor response acceleration time histories of the JMA Kobe Wave 100% (Excitation 3).

4. Monitoring Building Damage using Non-time Synchronization Devices

4.1 Damage evaluation method

Okada et al. [5] identified the maximum story drift angle of the building during vibration, by calculating the deformation amount at each measurement location from the integral of the acceleration history acquired by the seismographs that guarantee time synchronization. However, this method is not applicable to smartphones and breakers that do not guarantee time synchronization.

In this paper, procedure for building damage monitoring using seismometer devices that do not guarantee time synchronization is proposed that estimates the 1st story behavior using only the response acceleration record from the 2nd floor, based on an inverse response analysis in the frequency domain of the equivalent single-DOF system considering the plastic deformation behavior. The story drift angle (SDA) of the 1st story of the wooden house can be evaluated using the following equation:

$$\frac{y}{y''+y_0''}=\frac{-1}{\omega_0^2-i\left(2h\omega\omega_0\right)}=\frac{-\omega_0^2+i\left(2h\omega\omega_0\right)}{\omega_0^4+4h^2\omega^2\omega_0^2} \qquad (1)$$

$$\omega_0=2\pi/t_e$$

where

y'' is the relative acceleration of the 2nd floor;
y_0'' is the input acceleration;
y is the relative displacement of the 2nd floor;
t_e is the equivalent 1st natural frequency, taking into account the elasto-plastic behavior of the structure;
h is the equivalent damping constant, taking into account the elasto-plastic behavior of the structure.

The story drift angle is obtained by dividing y by story height. $y''+y_0''$ is equal to the response acceleration record of the 2nd floor. The equivalent damping constant h is evaluated from the following equation:

$$h=h_s\times\left(\frac{t_0}{t_e}\right)^2+h_{eq} \qquad (2)$$

$$h_{eq}=\frac{3\mu_e-2-\alpha_y}{12\pi\mu_e} \qquad \mu_e=\alpha_y\frac{t_e^2}{t_0^2}$$

where

h_s is the tangent stiffness proportional damping (= 0.03);
t_0 is the 1st natural frequency (elastic);
α_y is the stiffness reduction ratio (= 0.3).

The only unknown in the above equations is the equivalent 1st natural frequency t_e. In this paper, t_e is obtained from the peak frequency of the acceleration fourier amplitude spectrum ratio based on the acceleration records of the 1st and 2nd floors. The ratio can be calculated from acceleration records that are not time synchronized.

4.2 Comparison between experimental results and the proposed evaluation formula

Figures 8 to 11 show a comparison between the experimental results of the story drift angle (SDA) on the 1st story and the proposed evaluation formula (1). The red line shows the story drift angle history calculated from the integral of the acceleration history acquired by the seismographs (1st and 2nd floor LAN seismographs) that guarantee time synchronization. The blue dashed line is the proposed evaluation formula (1). The acceleration record of the 2nd floor uses the time history from the smartphone. The black dotted line indicates the maximum story drift angle based on the 3D image measurement system used in the E-Defense test. The evaluation accuracy of the proposed formula (1) is inferior to that using a multi-device that guarantees time synchronization. However, the proposed formula (1) mostly corresponds to the E-defense experiment results, and the accuracy of the proposed method was within tolerance.

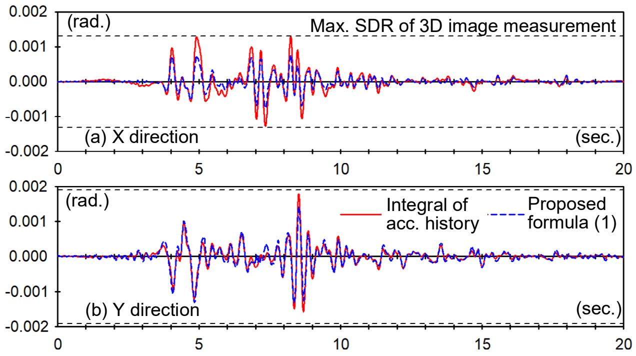


Fig. 8 – SDA of JMA Kobe 25% (Excitation 1).

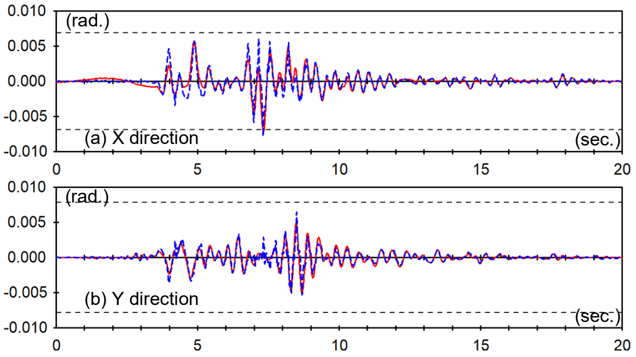


Fig. 9 – SDA of JMA Kobe 50% (Excitation 2).

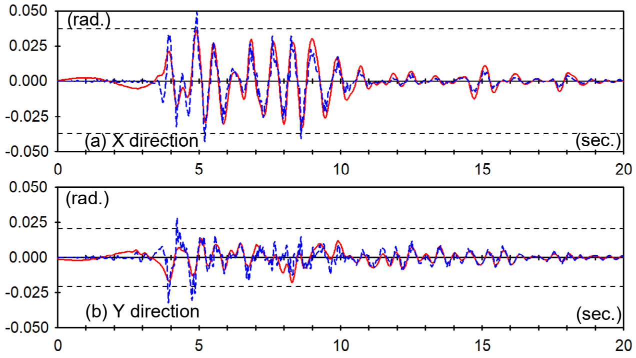


Fig. 10 – SDA of JMA Kobe 100% (Excitation 3).

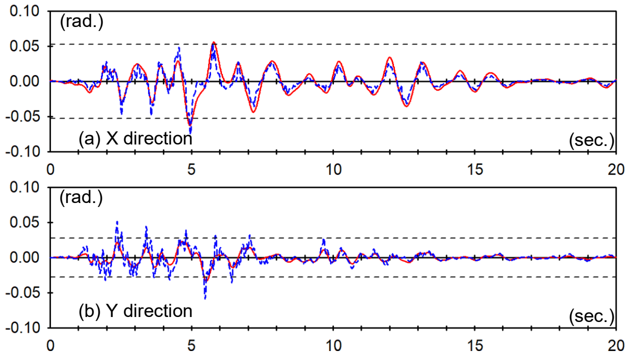


Fig. 11 – SDA of JR Takatori 100% (Excitation 4).

5. Conclusions

1) This paper verified the performance of the LAN strong-motion seismographs, smartphones, and seismic electric breaker, based on acceleration records from the E-Defense shaking table test of wooden houses. Smartphones and seismic electric breakers have the potential to be used to monitor damage in wooden houses. In particular, the breaker attached to the non-structural wall near the ceiling of the first story was almost equal to the response acceleration of the floor of the second story.

2) The authors proposed a procedure for building damage monitoring using seismometer devices that do not guarantee time synchronization. The proposed method estimates the first floor behaviour using only the response acceleration record from the second floor, based on an inverse response analysis in the frequency domain of the equivalent single-DOF system considering the plastic deformation behaviour.

3) The evaluation accuracy of the proposed method is inferior to that using a multi-device that guarantees time synchronization. However, the proposed method mostly corresponds to the E-Defense experiment results, and the accuracy of the proposed method was within tolerance.

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7. References

[1] Editorial Committee for the Report on the Hanshin-Awaji Earthquake Disaster (1998): *Report on the 1995 Hanshin-Awaji Earthquake disaster*, Japan. (in Japanese)

[2] Joint Editorial Committee for the Report on the Great East Japan Earthquake Disaster (2015): *Report on the 2011 Great East Japan Earthquake disaster*, Japan. (in Japanese)

[3] Sone A, Yamamoto A, Masuda A (1996): Identification of dynamic characteristics of structure and its change by using wavelet analysis of records of microtremor and response of structure on ordinary condition and during strong shock. *Journal of Structural and Construction Engineering (Transactions of AIJ)*, No. 490, pp. 65-72. (in Japanese)

[4] Saito S, Sugino M, Hayashi Y (2019): Evaluation of deformation dependency of primary natural frequency decrease rate of low-rise houses by microtremor measurement: on Japanese conventional wooden, light-gauge steel, and traditional wooden structure. *Journal of Structural and Construction Engineering (Transactions of AIJ)*, 757, 343-350. (in Japanese)

[5] Okada K, Morii T, Shiraishi M (2017): Verification of all story seismic building response estimation method from limited number of sensors using large scale shaking table test data. *Journal of Technology and Design (Transactions of AIJ)*, Vol. 23, No. 53, pp.77-82. (in Japanese)

[6] Hayashi K, Saito T, Horioka T, Sato E (2019): Implementation of real-time seismic diagnostic system on emergency management center buildings: system introduction and operational status on municipal government office buildings. *Journal of Civil Structural Health Monitoring (Springer)*, 1-13.